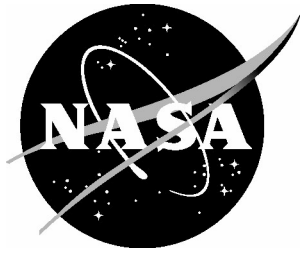


NASA/CR-2007-214540



# A Procedure for Modeling Structural Component/Attachment Failure Using Transient Finite Element Analysis

*Andrew E. Lovejoy*  
*Analytical Services & Materials, Inc., Hampton, Virginia*

---

January 2007

## The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

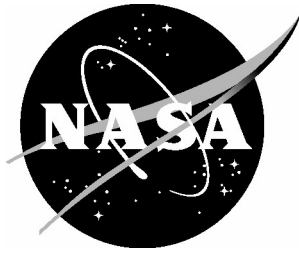
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Help Desk at (301) 621-0134
- Phone the NASA STI Help Desk at (301) 621-0390
- Write to:  
NASA STI Help Desk  
NASA Center for AeroSpace Information  
7115 Standard Drive  
Hanover, MD 21076-1320

NASA/CR-2007-214540



# A Procedure for Modeling Structural Component/Attachment Failure Using Transient Finite Element Analysis

*Andrew E. Lovejoy*

*Analytical Services & Materials, Inc., Hampton, Virginia*

National Aeronautics and  
Space Administration

Langley Research Center  
Hampton, Virginia 23681-2199

Prepared for Langley Research Center  
under Contract NNL04AA10B

---

January 2007

Available from:

NASA Center for Aerospace Information (CASI)  
7115 Standard Drive  
Hanover, MD 21076-1320  
(301) 621-0390

National Technical Information Service (NTIS)  
5285 Port Royal Road  
Springfield, VA 22161-2171  
(703) 605-6000



## Table of Contents

Table of Contents.....	1
List of Figures.....	2
List of Tables.....	4
Abstract .....	5
Introduction .....	5
Transient Failure Analysis Procedure.....	5
Modeling Method .....	5
Load Time History.....	6
Direct or Modal Transient Analysis .....	8
Procedure Definition.....	9
Simple Example – Cantilevered Box Structure.....	17
Static Analysis Models .....	17
Linear Analysis Response .....	18
Transient Loading.....	18
Modal Analysis.....	18
Transient Analysis .....	18
Comparison of Linear and Transient Response .....	19
Real World Example – AA587 Vertical Tail Plane.....	27
Physical Damage .....	27
Initial Failure .....	28
Transient Failure Analysis .....	28
Conclusion.....	35
References .....	36

## List of Figures

Figure 1: Load method with initially applied load factors of 1.0 .....	10
Figure 2: Load method with ramped load factors.....	10
Figure 3: Typical connection forces (point 1 of simple example) for an undamped transient analysis using load method of Figure 1.....	11
Figure 4: Typical connection forces (point 1 of simple example) for a moderately damped transient analysis using load method of Figure 1.....	11
Figure 5: Typical connection forces (point 1 of simple example) for a heavily damped transient analysis using load method of Figure 1.....	12
Figure 6: Comparison of typical connection total force (point 1 of simple example) for transient analyses with various degrees of damping using load method of Figure 1.....	12
Figure 7: Typical connection forces (point 1 of simple example) for an undamped transient analysis using load method of Figure 2.....	13
Figure 8: Typical connection forces (point 1 of simple example) for a moderately damped transient analysis using load method of Figure 2.....	13
Figure 9: Comparison of typical connection total force (point 1 of simple example) for undamped and moderately damped transient analyses using load method of Figure 2.....	14
Figure 10: Representative time-dependent load history for structure having two load sets .....	14
Figure 11: Comparison of connection x-force (point 2 of simple example) for undamped direct and modal transient analyses using load method of Figure 2.....	15
Figure 12: Comparison of connection y-force (point 2 of simple example) for undamped direct and modal transient analyses using load method of Figure 2.....	15
Figure 13: Comparison of connection z-force (point 2 of simple example) for undamped direct and modal transient analyses using load method of Figure 2.....	16
Figure 14: Comparison of connection total force (point 2 of simple example) for undamped direct and modal transient analyses using load method of Figure 2.....	16
Figure 15: Transient failure analysis procedure .....	17
Figure 16: Cantilevered box structure example with pinned corner point supports and tip corner loads (kips) (Model 1).....	22
Figure 17: Loads (kips) and boundary conditions for the example model with one support removed (Model 2).....	22
Figure 18: Support point numbering convention.....	23
Figure 19: Loads (kips) and boundary conditions for the example model with one support replaced by the reaction force (Model 2) .....	23
Figure 20: Linear static analysis reaction forces (kips) for loading/BCs of Figure 16.....	24
Figure 21: Linear static analysis reaction forces (kips) for loading/BCs of Figure 19.....	24
Figure 22: Linear static analysis reaction forces (kips) for loading/BCs of Figure 17.....	24
Figure 23: Frequencies and mode shapes for Model 1 .....	25
Figure 24: SPC reaction force response at point 1 for load method shown in Figure 2 .....	26
Figure 25: SPC reaction force response at point 2 for load method shown in Figure 2 .....	26
Figure 26: SPC reaction force response at point 3 for load method shown in Figure 2 .....	27

Figure 27: Fin and rudder hinge line damage of AA587 .....	30
Figure 28: Rudder damage of AA587.....	31
Figure 29: Sketch of rudder damage of AA587 .....	32
Figure 30: Primary loading on VTP during accident event .....	33
Figure 31: Fuselage tail section and VTP finite element model and coordinate system .....	33
Figure 32: Left rear yoke forces .....	34
Figure 33: Approximation plot of left rear yoke force for subsequent failure analyses (markers indicate values used in tabular load input) .....	34
Figure 34: Inner surface rudder skin strains, $\epsilon_{xx}$ , in region of hinge fitting #1 .....	35
Figure 35: Transient failure sequence (green number indicates sequence for both static and transient analysis, orange indicates static, and blue indicates transient).....	35

## **List of Tables**

Table 1: Linear analysis connection force (lbs) comparison for cantilever box structure with no failed supports and one failed support (point 4, see Figure 18).....	20
Table 2: Transient failure analysis connection forces (lbs) for the cantilever box structure with one failed support (point 4, see Figure 18).....	21
Table 3: Comparison of maximum connection forces (lbs) and transient dynamic load factor for the cantilever box structure with one failed support (point 4, see Figure 18) .....	21
Table 4: Lug and shear yoke allowable strengths.....	29
Table 5: Linear analysis lug and yoke forces, in global coordinate system, for the Max C load condition .....	29

## **Abstract**

Structures often comprise smaller substructures that are connected to each other or attached to the ground by a set of finite connections. Under static loading, one or more of these connections may exceed allowable limits and be deemed to fail. Of particular interest is the structural response when a connection is severed (failed) while the structure is under static load. A transient failure analysis procedure was developed by which it is possible to examine the dynamic effects that result from introducing a discrete failure while a structure is under static load. The failure is introduced by replacing a connection load history by a time-dependent load set that removes the connection load at the time of failure. The subsequent transient response is examined to determine the importance of the dynamic effects by comparing the structural response with the appropriate allowables. Additionally, this procedure utilizes a standard finite element transient analysis that is readily available in most commercial software, permitting the study of dynamic failures without the need to purchase software specifically for this purpose. The procedure is developed and explained, demonstrated on a simple cantilever box example, and finally demonstrated on a real-world example, the American Airlines Flight 587 (AA587) vertical tail plane (VTP).

## **Introduction**

Structures often comprise smaller substructures that are connected to each other or attached to the ground by a set of finite connections. During static loading, these connection forces are defined by forces within connection members or as reaction loads in single- or multi-point constraints (SPCs or MPCs), depending on the type of connection and the modeling method utilized. In general, at the connection nodes there is some combination of net forces and/or moments present to maintain equilibrium of the structure. Of particular interest is the structural response when a connection is severed (failed) while the structure is under static load. Specifically, how do the dynamic loads seen at the remaining connection points and internal to the structure compare to the loads computed with a static analysis of the same structure with a severed connection? In other words, is there dynamic load overshoot at the remaining connections and/or internal to the structure that can lead to an assessment of the structure that differs from that obtained from static analysis after a connection or component has failed? Is it possible to approximate the response of a complex structure by analogy with the performance of a single-degree-of-freedom system subjected to step or ramp loading? A quantitative evaluation of the dynamic response is required to assess the response when a finite connection fails, and to indicate what modeling and analysis are required to provide this dynamic response assessment. Although software analysis packages exist that can handle such a problem, a simplified modeling and analysis procedure is needed. A procedure is developed herein that permits the required dynamic analysis using a specific application of the standard transient analysis method present within basic finite element software.

## **Transient Failure Analysis Procedure**

### **Modeling Method**

The transient failure analysis procedure requires a model that allows determination of the time-dependent connection point forces and/or moments. Determination of the connection forces/moments is accomplished using single-point constraints (SPCs) and multi-point constraints (MPCs). SPCs are used to connect the structure to ground, and MPCs are used to connect points that are internal to the structure. Failures internal to the structure, other than a discrete connection, can be modeled using multiple pairs of duplicate nodes and treating each pair of nodes as a discrete connection. Failure within the component is then represented as a series of discrete component failures. The difficulty is determining where to locate

the internal duplicate nodes to simulate internal failures because some prior knowledge of the response is required. Discrete connections are more straight forward since their locations are well known, so they can be replaced by the SPC or MPC at the outset with little difficulty. The SPC and MPC output values at each connection can be directly compared to failure allowables to identify connection failures. An SPC or MPC must be included at every location where a failure will be introduced. The SPC and MPC values are used to generate the time-dependent force/moment history described in the next section.

## **Load Time History**

The transient failure analysis procedure requires knowledge of the time-dependent load history for the structure. The time-dependent load history is the definition of the loads that act upon the structure as a function of time. Two or more load sets are created from the load history so that load transfer through a connection can be eliminated to represent the connection failure. Connection failures are simulated by removing the failed connection (SPC or MPC), and replacing it with the constraint load history and reanalyzing. The constraint values are applied as time-dependent loads, mimicking the constraint reaction up to the point of failure, at which time the load is quickly reduced to zero to simulate failure. The analysis is continued until failure of another connection is indicated. After each “failure,” the constraint force history for that connection is extracted and converted into a load set and the structural analysis re-initiated at time  $t=0$ . In general, all loads associated with the structure may be time variant. However, since this report considers structures for which a failure occurs under static load, it is assumed that the load sets associated with applied loads are time invariant and will remain constant throughout the entire analysis process. On the other hand, the set(s) representing failure(s) are time variant.

Initially, to determine whether a failure will occur, a static analysis must be conducted. The load condition under which the first failure occurs becomes the initial point in the actual load history, and is referred to herein as the initial failure load. However, the total load history required to perform the transient failure analysis will generally contain a load introduction portion. This load introduction portion is required within the transient analysis to allow the structure to attain a static equilibrium state prior to introducing the first failure. If the analysis code permits the transient analysis to start from a static solution, then the load introduction portion of the time history is not required. The remainder of the load time history comprises the loads experienced post-first-failure, which constitutes the actual time-dependent load history for the structure.

In order to determine the time-dependent load history, it is, in general, necessary to represent the load introduction using a ramp function for all load sets, slowly increasing the loads to 100% of the initial failure load. This is followed by a brief period of uniform loading to establish “static” equilibrium, followed by the release of the load set(s) associated with failure(s). It is the responsibility of the analyst to develop the load introduction portion of the load history based upon their experience and the problem of interest. The time required for the ramp and uniform load portions will be highly dependent upon the problem, so the analysis may have to experiment to determine the most reasonable introduction portion of the load history. The reasoning behind this procedure is made clear in the following discussion.

Consider two methods of applying the load as shown in Figures 1 and 2. In Figure 1, the total load is applied at time  $t=0$ , and then the load for the failed connection is reduced to zero. In Figure 2, the load is applied gradually until the full load at first failure, the initial failure load, is reached. The load is kept constant for a period of time, and then the load for the failed connection is reduced to zero. For either of these loading methods, the transient analysis conducted may or may not include structural damping, the importance of which is described subsequently.

The simple example structure described and analyzed in the next section is used to demonstrate and compare the transient analysis load application methods shown in Figures 1 and 2. Using load application method 1 defined in Figure 1, a transient analysis was performed with failure being simulated at time  $t=10$  seconds. The load introduction portion of this load history is then defined to be that portion of the load history that is prior to  $t=10$  seconds. The results for a representative connection on the structure, as analyzed using load application method 1, are shown in Figures 3 to 5 for undamped, moderately damped

and heavily damped conditions. The response of the system comprises the myriad of modal responses that are possible. As seen in Figure 3, the undamped case can result in a very erratic response that is difficult to interpret. When damping is included, the higher frequency response is removed and the overall response tends to become stable with time, as seen in Figures 4 and 5. The total force response of the connection for these three damping cases is compared in Figure 6, where the pre- and post-failure static response values are represented by the short and long gray dashed lines, respectively. Several key factors are observed in Figure 6. First, the response before and after failure is centered around the static value in the respective region, that is, the average response is the static analysis response. Second, adding damping smoothes the response curve and eliminates high-frequency oscillations. Last, as damping is increased, the maximum force value decreases, which during the transient failure analysis results in a lower overshoot value that may not accurately reflect the true overshoot. Therefore, damping should be included in the transient analysis, but it should be as small as possible and limited to a value that will smooth the curve satisfactorily. The value used to introduce damping depends upon how damping is implemented in the software (i.e., what parameter(s) are specified) and the structure, so experimentation by the analyst may be required to determine proper damping for a given problem.

Next, consider the load method depicted in Figure 2 where the failure is simulated at time  $t=12$  seconds. The undamped response of a representative connection is shown in Figure 7. In contrast to method 1, the response observed from an analysis using method 2 is relatively stable and smooth up until the introduction of the failure. This response is a result of the gradual introduction of load so that the oscillatory response is minimized. After the failure is introduced, however, the oscillatory nature of the response is again seen. The response at the same location when a moderate amount of damping is introduced is represented in Figure 8. Figure 9 shows a comparison of the undamped and moderately damped total force response of the connection, with the pre- and post-failure static response total connection force values represented in the figure by the short and long gray dashed lines, respectively. From the figures, it is seen that a long ramp period virtually eliminates any transient response due to the initial load application even when structural damping is not present, indicating that the ramped load method depicted in Figure 2 should be used to perform the transient failure analysis. The effect of the ramp is as if a static load is applied to obtain static equilibrium, then one of the static loads is removed to simulate failure of a support or connection, resulting in the transient response. However, it is recommended that a small amount of damping should be included to minimize high frequency response to yield a more smooth and readable response.

An example of what the load cycle would look like for a structure with one invariant load set (load set #1) and a single connection failure load set (load set #2) is shown in Figure 10. The two load sets start at zero load at the initial time,  $t_i$ , then ramp up to 100% of initial failure load at  $t_1$ . The loads remain steady for a short time until load set #2 is reduced to zero at time  $t_2$  to simulate the failure. The analysis then continues for a short time to  $t_f$ . The time  $t_f$  should be sufficiently after  $t_2$  such that the maximum connection loads are observed or the next connection failure occurs. The length of the ramp between times  $t_i$  and  $t_1$  is determined by the period of the fundamental frequency of the system and should be sufficiently long to eliminate transient response during the ramp time.

Alternatively, in some analysis codes, it is possible to start the transient analysis directly from a static analysis solution, and thus remove the load introduction portion of the time-dependent load history. In this case a static analysis would be conducted with 100% of the initial failure load. The transient analysis will start directly, equivalent to time  $t_2$  in Figure 10, with load set 2 reduced to zero to simulate the failure. This static/transient implementation capability was introduced into MSC/NASTRAN 2004 [1]. Such a procedure is desired because of the reduced computation time resulting from the elimination of the load introduction portion of the time history, represented by the portion of the plot between times  $t_i$  and  $t_2$  in Figure 10.

NASTRAN was used in the development and demonstration of this transient failure analysis method, therefore, an additional note on the loading history is required. In NASTRAN transient analysis, the load vector is taken to be the average of three adjacent time steps. Averaging of the load vector imposes the constraint that there cannot be a step change in load history because a step results in two load values

being assigned to the same time step, and NASTRAN cannot handle multiple load values for a single time value (i.e., the tabular force/time table must represent a single-valued function). As a result, when modeling the failure of a connection by reducing the load to zero, it is necessary to make a very steep ramp rather than a step drop. The steepness of this ramp is dictated by the frequency response of the structure, and the ramp duration must be shorter than the time required for any anticipated response to occur, say one tenth of the period of the highest frequency of interest.

The time-dependent load history sets for failed connections are used to simulate failures. Load history sets are specified throughout the analysis using tabular input with the actual connections (SPC or MPC) removed from the model. Consider Figure 10, where load set 2 represents the load history for a failed connection. Load set 2 is generated by conducting a static analysis of the intact (pristine) structure to determine the force in the connection (SPC or MPC) at the initial failure load. For the initial failure, the load history is simply constructed by assigning a value of zero at  $t_i$ , and the value at initial failure at times  $t_1$  and  $t_2$  in the figure. For failures subsequent to first failure, the time dependent load history will be more complex in nature (recall Figures 3 through 9), but will still be specified during the analysis using tabular input. The accuracy of the tabular representation is dependent upon the number of points used to represent the load history. Choosing the correct number of points to represent this load history to the desired accuracy is the responsibility of the analyst. In NASTRAN, using tabular input results in the load history being represented by a piece-wise linear function.

Other code-specific analysis parameters can be specified for the transient analysis when effects such as those associated with the structural damping are desired to be included. The damping ratio and the dominant frequency for which damping occurs, usually the fundamental frequency (frequency of the first natural mode), are also specified. Specifics associated with the transient analysis in NASTRAN can be found in References 2 and 3.

### **Direct or Modal Transient Analysis**

As previously stated, the elimination of a connection load is necessary in order to represent a connection failure. An actual connection, represented by an SPC or MPC, is being replaced by a load history to simulate failure, resulting in a model that is physically changed. This change in the physical model leads to two consequences:

1. When connection loads indicate failure of a connection, the SPC/MPC representing the connection is replaced by a tabular input time history load set containing the SPC/MPC force history at the connection point. Therefore a restart is not possible after each failed connection is identified because the number of degrees of freedom and stiffnesses in the restart will not match those in the previous analysis. As a result, the analysis must be started from the beginning (the start of the ramp or the static analysis) each time after a failed connection is identified, with all failed connections being replaced by their time history load sets.
2. Modal transient analysis is not a feasible method to use in the transient failure analysis. The modeling approach for failure simulation replaces physical connections between components with equivalent force histories. The modal response of the model with simulated connections (force histories) does not provide frequencies and mode shapes that are equivalent to the model with the actual SPC/MPC connections (the pristine structure). The modes are representative of the final configuration so they can represent the response very well after the last connection fails. However, as more connections failures are modeled, it is much more difficult for the mode shapes of this simulated multiple-connection-failure structure model to represent the response prior to the final failure modeled in the analysis. As it is difficult for the mode shapes of the pristine structure to represent the response of the structure with connection failures, similarly, it is difficult for the mode shapes of the structure with failures to represent the response for the pristine structure and structure with fewer failures. Figures 11 to 14 show a connection's x-, y- and z-direction forces and total force response comparisons, respectively, for a direct transient analysis and two modal transient analyses utilizing 10 and 32 modes. The connection is in a simple model (the



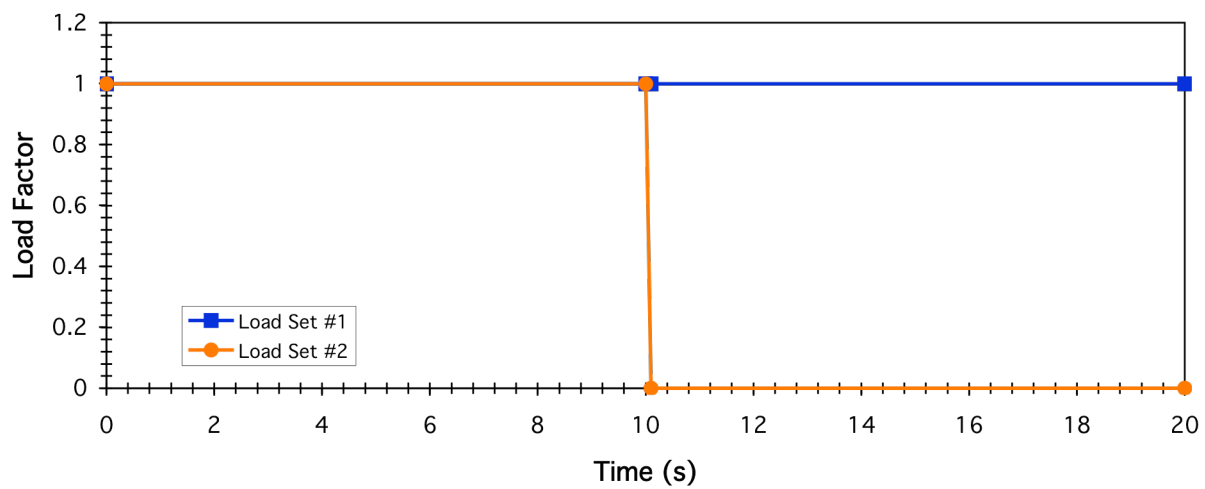
cantilevered box structure simple example of the next section) in which only one connection failure is modeled at  $t=12$  seconds. Notice that even for this simple example, with only one failure modeled, the 10 mode modal analysis can not represent the response accurately prior to the failure being represented. The 32 mode solution performs much better, but is still not very good for the time prior to first failure at  $t=12$  seconds. When more connection failure locations are modeled, the response will show similar errors throughout the sequence up until the final failure is introduced. For a given number of modes used in the analysis, these errors will increase with an increasing number of modeled failures. Therefore, the modal transient analysis will generally require a very large number of mode shapes, and even then may not be sufficient to retain accuracy throughout the time history. Consequently, the more computationally time-consuming direct transient analysis is required to perform the transient failure analysis procedure.

Examination of the direct transient and modal analysis methods has shown that the direct transient analysis method should be used. Additionally, the analysis must be reinitiated (at  $t=0$ ) after each successive failure is identified and modeled.

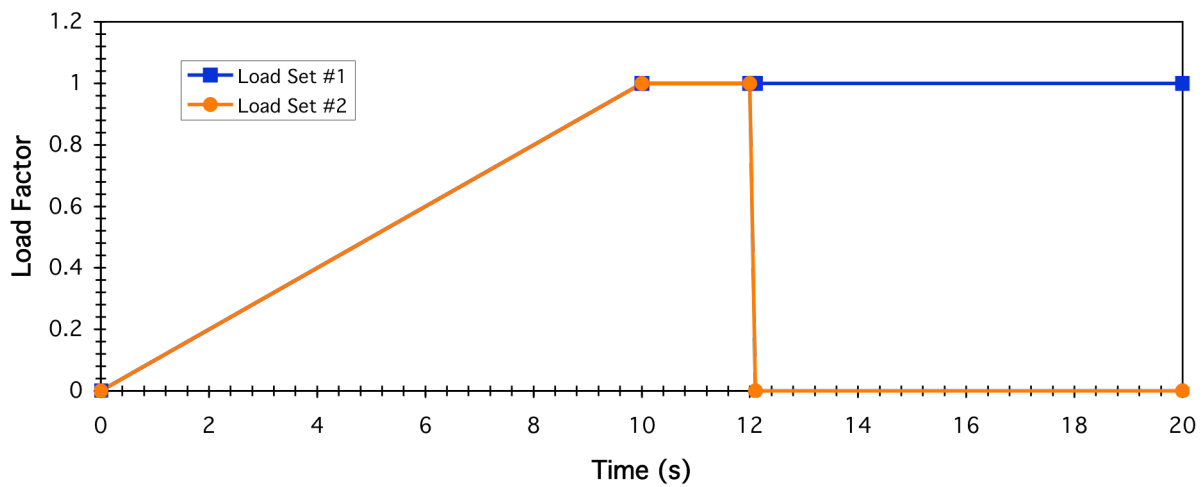
### **Procedure Definition**

Based upon the basic sequence and restrictions described above, the transient failure analysis is conducted using the procedure shown schematically in Figure 15 and described as follows:

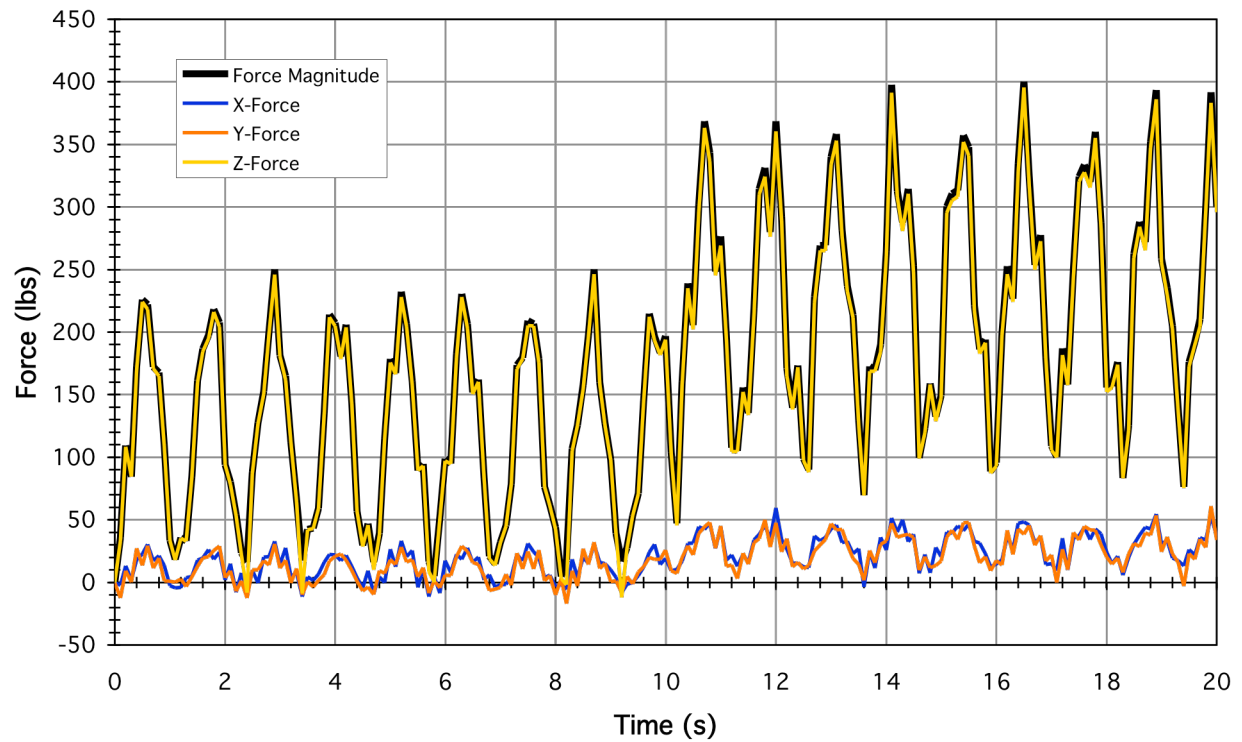
1. Conduct a normal modes analysis to determine the natural frequency response.
  - a. Use the fundamental frequency period to determine the load introduction ramp duration and "static" portion duration of the load time history. It is suggested that the ramp duration exceed 10 periods and the "static" portion duration exceed 2 periods.
  - b. Use the fundamental frequency to determine the structural damping parameters.
  - c. Use the period of the highest frequency for which response is expected to determine the length of the steep ramp used to reduce the failed component load set to zero.
2. Conduct a static analysis to establish that a connection will fail under static load and determine the initial failure load.
3. Replace the connection in the model with its entire time-dependent load history from the pristine structure up to the time of connection failure. This requires, for example, removing an MPC and applying equal and opposite loads to the nodes that were previously attached via the MPC.
4. Conduct the direct transient analysis starting from  $t=0$  for the pristine structure, and continue the analysis to some time after the last identified connection failure is simulated. The amount of time the analysis needs to continue after the last identified failure is simulated is problem dependent, but it should be sufficiently long to encompass the next component failure or show that additional failures will not occur.
5. Determine the next failure occurrence or if no additional failures will occur.
6. Repeat steps 3-6 until the failure sequence is complete.



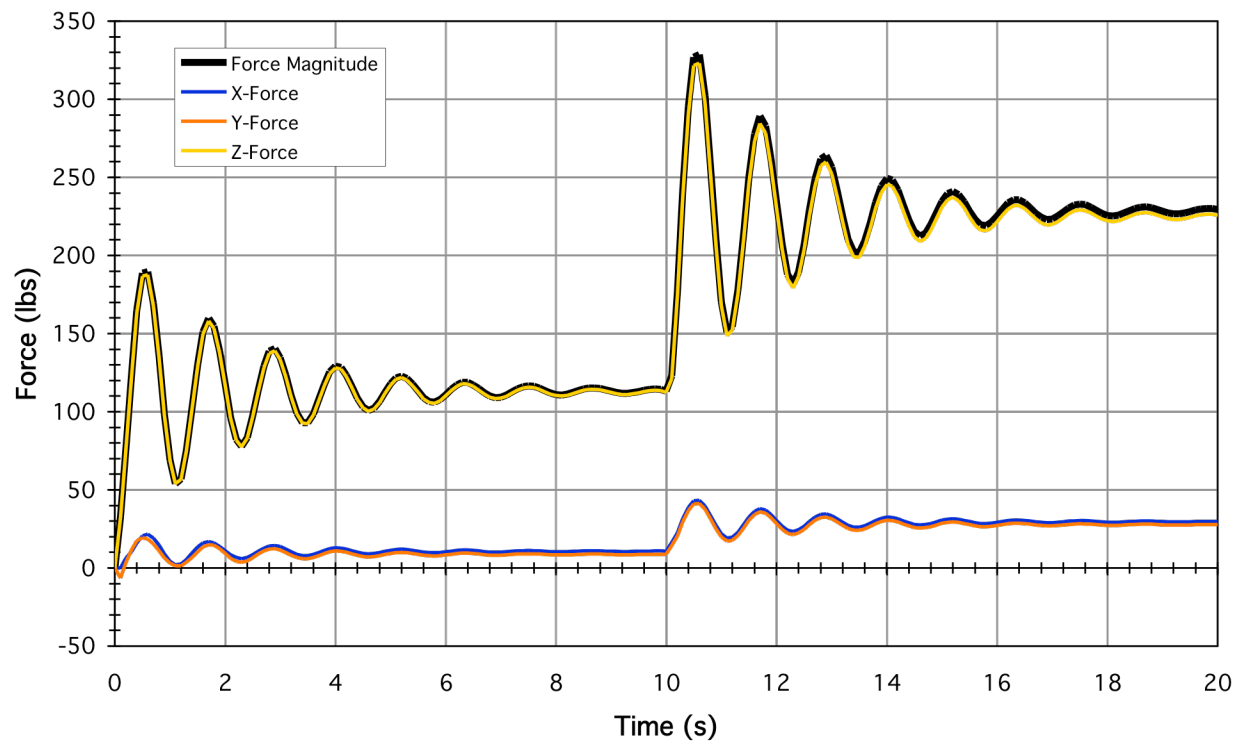
**Figure 1: Load method with initially applied load factors of 1.0**



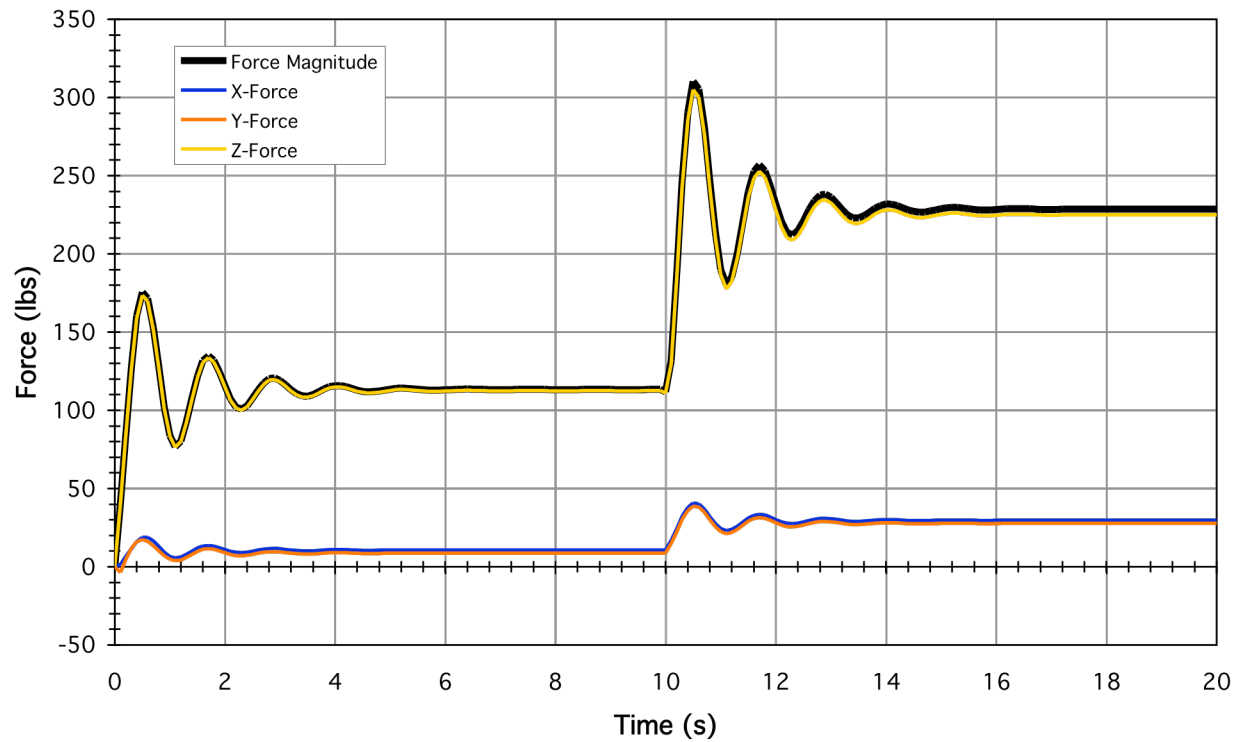
**Figure 2: Load method with ramped load factors**



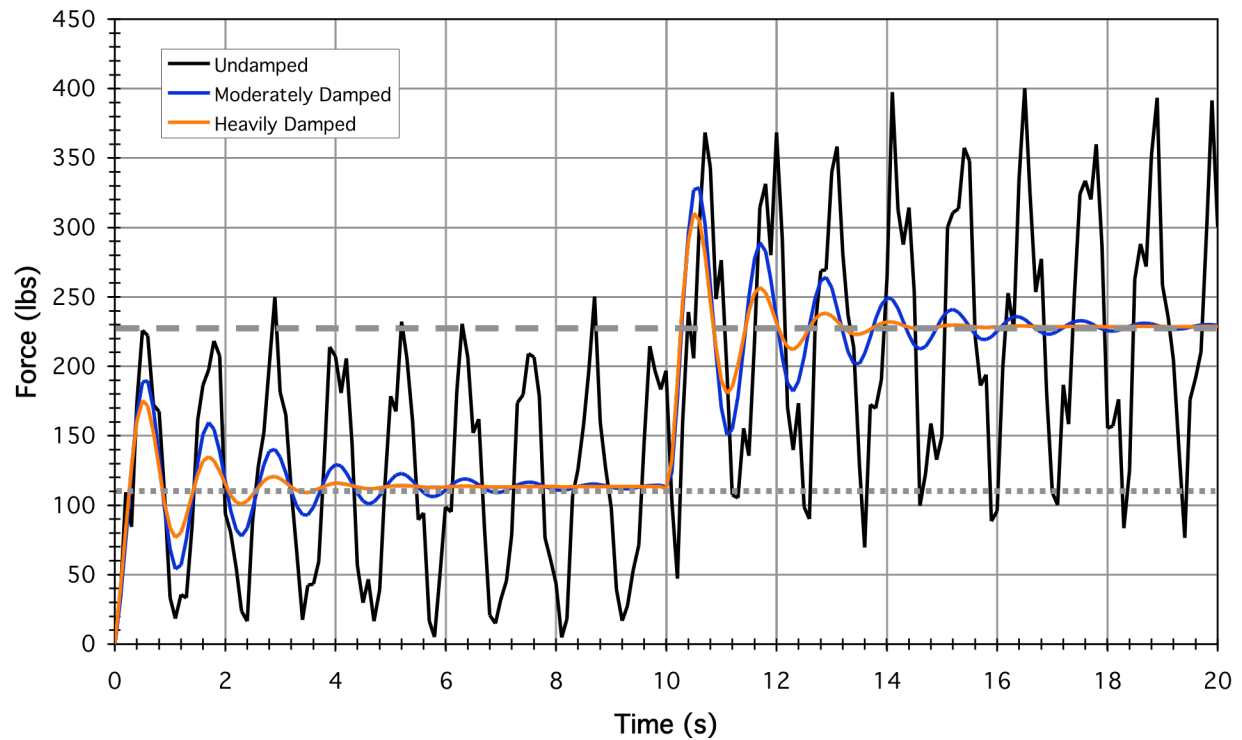
**Figure 3: Typical connection forces (point 1 of simple example) for an undamped transient analysis using load method of Figure 1**



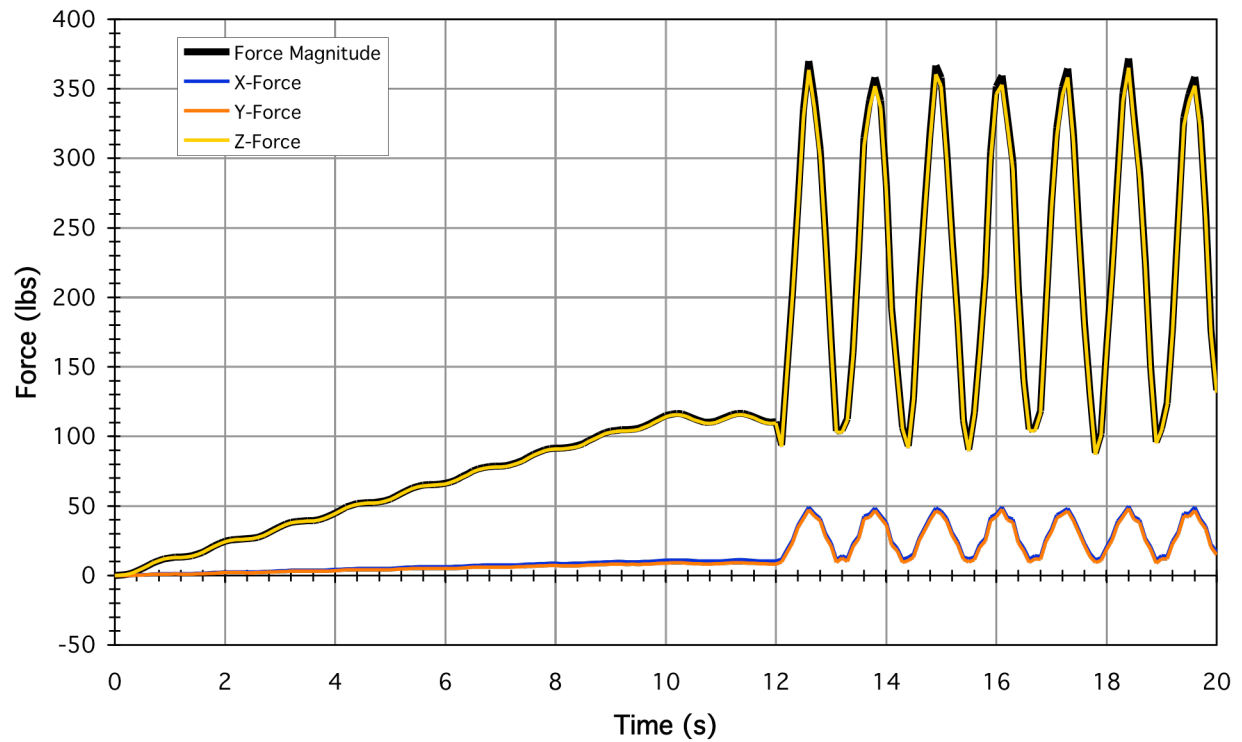
**Figure 4: Typical connection forces (point 1 of simple example) for a moderately damped transient analysis using load method of Figure 1**



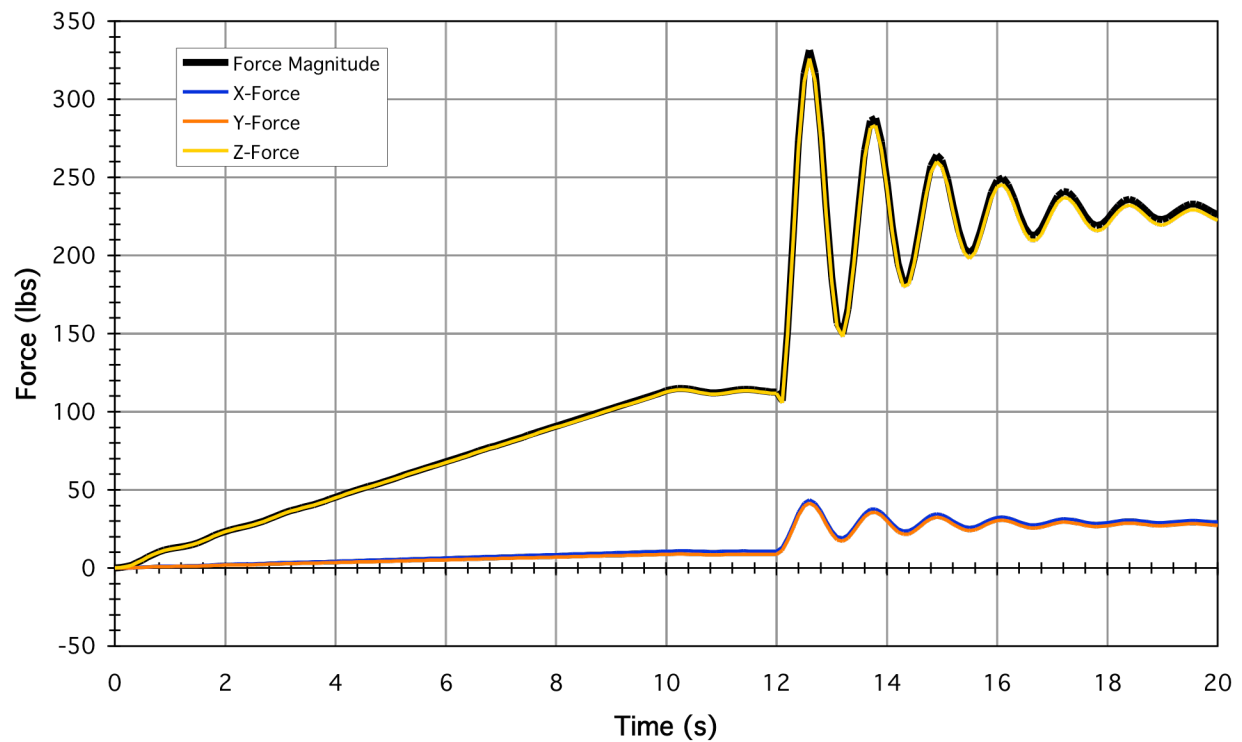
**Figure 5: Typical connection forces (point 1 of simple example) for a heavily damped transient analysis using load method of Figure 1**



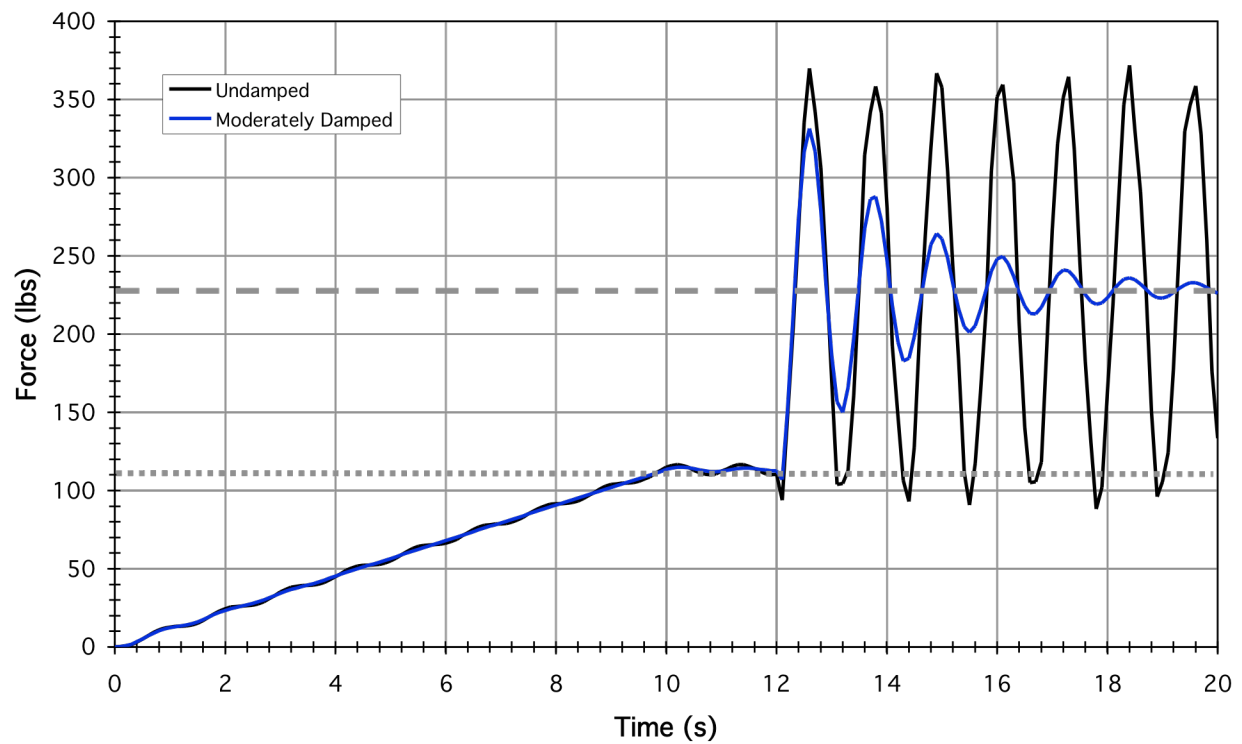
**Figure 6: Comparison of typical connection total force (point 1 of simple example) for transient analyses with various degrees of damping using load method of Figure 1**



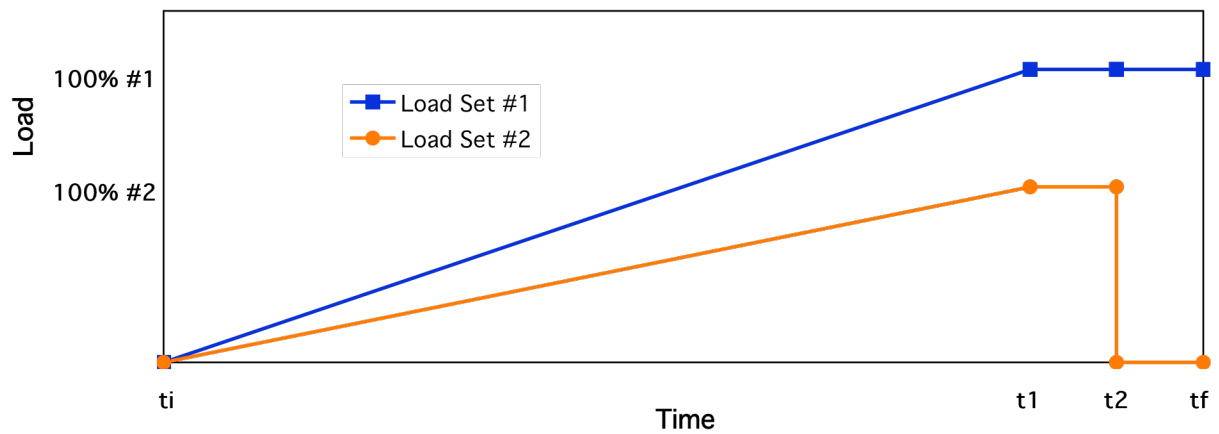
**Figure 7: Typical connection forces (point 1 of simple example) for an undamped transient analysis using load method of Figure 2**



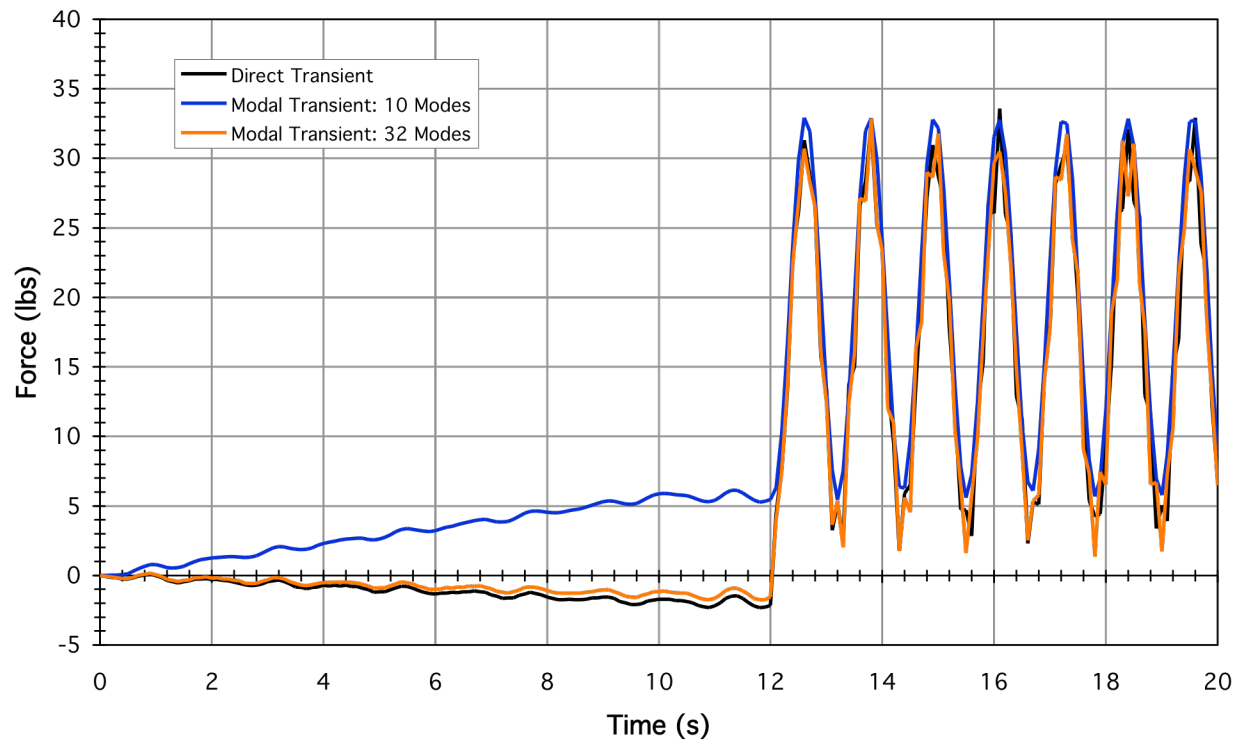
**Figure 8: Typical connection forces (point 1 of simple example) for a moderately damped transient analysis using load method of Figure 2**



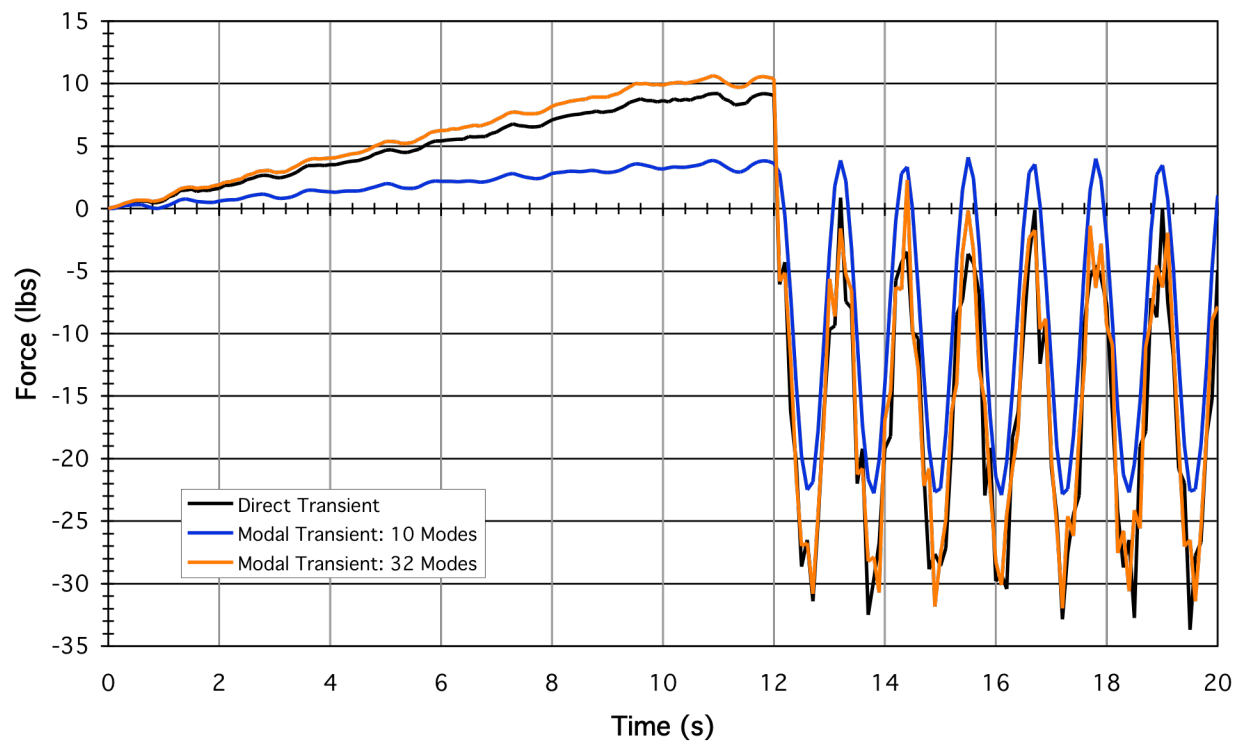
**Figure 9: Comparison of typical connection total force (point 1 of simple example) for undamped and moderately damped transient analyses using load method of Figure 2**



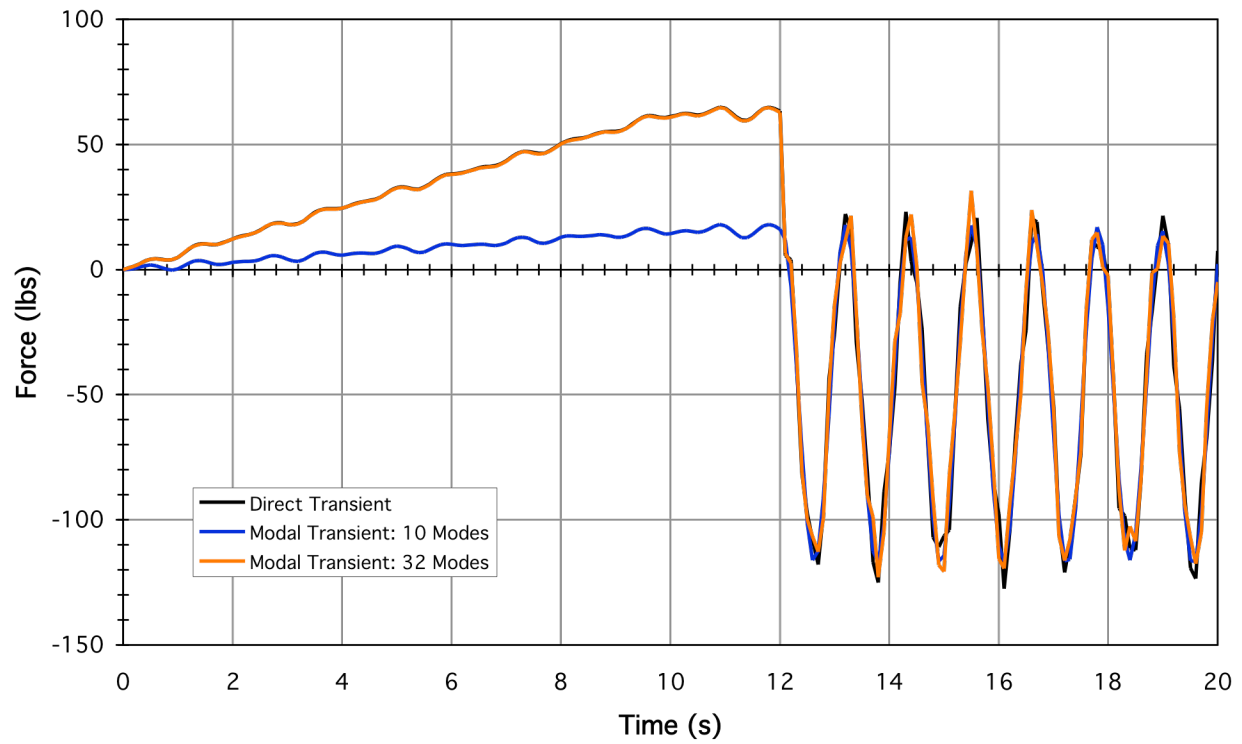
**Figure 10: Representative time-dependent load history for structure having two load sets**



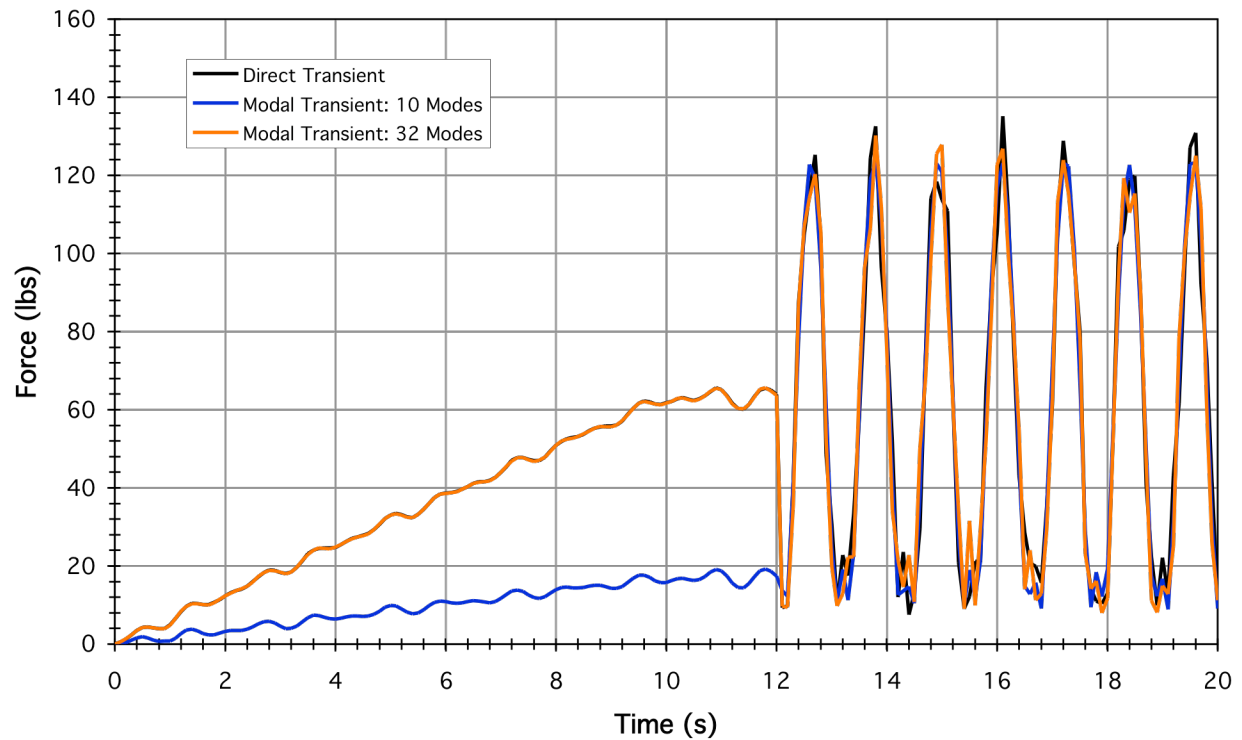
**Figure 11: Comparison of connection x-force (point 2 of simple example) for undamped direct and modal transient analyses using load method of Figure 2**



**Figure 12: Comparison of connection y-force (point 2 of simple example) for undamped direct and modal transient analyses using load method of Figure 2**

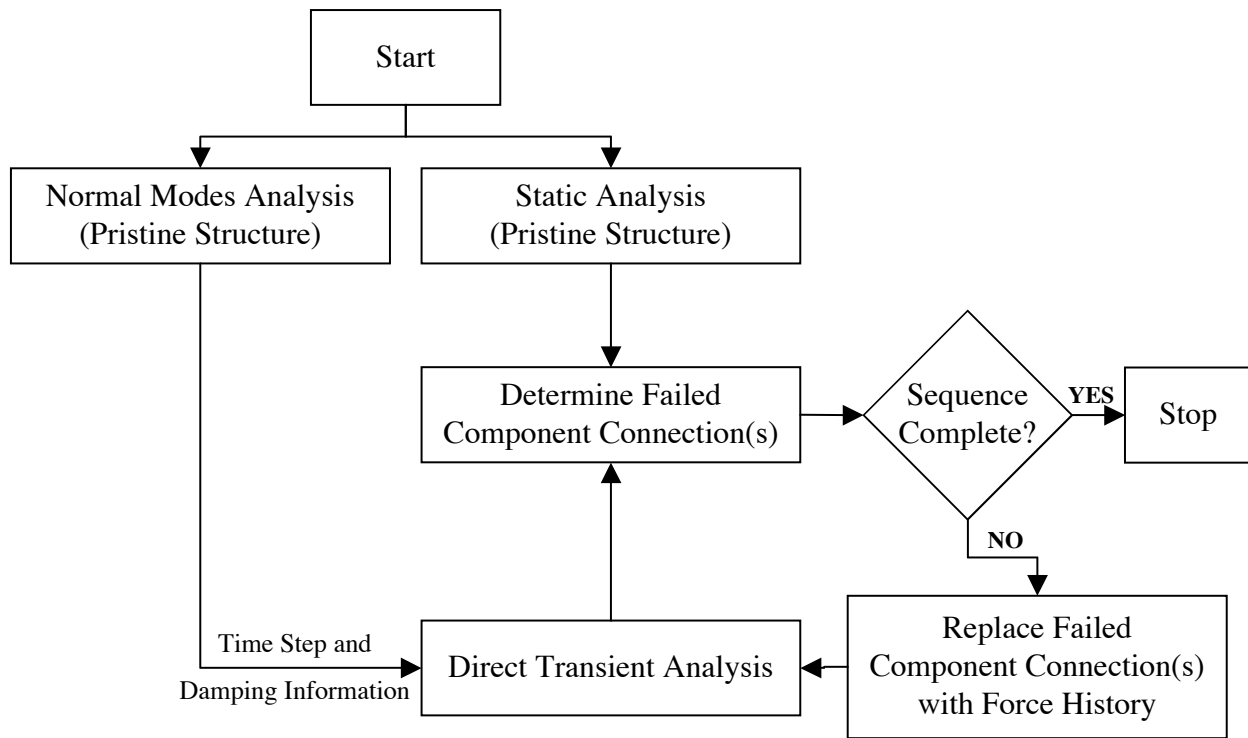


**Figure 13: Comparison of connection z-force (point 2 of simple example) for undamped direct and modal transient analyses using load method of Figure 2**



**Figure 14: Comparison of connection total force (point 2 of simple example) for undamped direct and modal transient analyses using load method of Figure 2**





**Figure 15: Transient failure analysis procedure**

## Simple Example – Cantilevered Box Structure

### Static Analysis Models

A simple example model is used to test/demonstrate the procedure. The example model structure constitutes a cantilevered box structure that is connected to 4 pinned point supports at the base corners as shown in Figure 16 (model 1). All components in the model are constructed from aluminum ( $E=10000$  ksi,  $\nu=0.3$ ,  $\rho=0.003$  slugs/in<sup>3</sup>). The box structure has a square cross-section that is 10 inches along each edge, and is 50 inches long. It consists of four “skins” that are 0.1 inches thick, and ten equal spaced “ribs” that are 0.06 inches thick (nine internal and one closeout at the load (free) end). It also has stringers running along its length at each corner ( $A=1. \text{ in}^2$ ,  $I_{11}=I_{22}=0.0833 \text{ in}^4$ , and  $J=0.1667 \text{ in}^4$ ), and there are beams representing rib flanges running around the circumference of the box at each rib ( $A=0.25 \text{ in}^2$ ,  $I_{11}=I_{22}=0.0003255 \text{ in}^4$ , and  $J=0.000651 \text{ in}^4$ ). At each point support, the three translations are restrained so that only reaction forces are developed at each support (they are modeled to represent pinned connections so there are no reaction moments). The applied loads (in kips) and boundary conditions are shown in Figure 16. Loading is such that the response is primarily bending, with some torsion provided by the 11.18 kip load that had a -5 kip load in the y-direction and a -10 kip load in the x-direction.

A second model of this cantilevered box structure is developed to examine the static solution after one connection is failed and to verify the use of load sets to represent the connection. The second model is generated by removing one of the support constraints so that the structure is pinned at three points, as shown in Figure 17 (model 2). The numbering of the support points is shown in Figure 18, with point 4 representing the failure location where the SPC was removed. This model with the SPC removed represents a single connection failure, and is used to determine the reaction forces at the remaining connections under static load that are compared to the reaction loads calculated during the transient analysis.

## Linear Analysis Response

The response of interest in this example is the reaction force set that is generated at the connection points. A static analysis of model 1 (Figure 16) results in the reaction forces shown in Figure 19. The ultimate goal is to fail one support in order to examine the transient response. To represent the support failure in the transient analysis, the constraint boundary conditions at the connection are replaced with the reaction force components. Figure 19 shows model 2 with the failed connection total reaction force applied at point 4. Static analyses of model 1 with the boundary conditions and loads shown in Figure 16 and model 2 with the boundary conditions and loads shown in Figure 19 verified that the two analyses are statically equivalent. Reaction forces for these two static analyses using models 1 and 2 are shown in Figures 20 and 21, respectively. Static equivalence of these two analyses is a necessary requirement for the transient analysis procedure that follows since the transient failure analysis procedure replaces actual connections with equivalent load sets.

Since it is desired compare the overshoot of the reaction forces from the transient analysis to the linear static analysis reaction forces, a static analysis for the structure with the failed support removed is conducted. The static analysis reaction forces for model 2 with the boundary conditions and loads shown in Figure 17 are shown in Figure 22. These reaction forces are used for the comparison to the dynamic reaction forces calculated by the subsequent transient analysis. It is expected that when the dynamic analysis is performed, when the statically-loaded structure is subjected to a failure of one support, that the restraining loads will “overshoot” the static analysis values shown in Figure 22. A single-degree-of-freedom system subjected to a step load is considered as a first approximation. Recall that for a single-degree-of-freedom system with step input, the overshoot (dynamic load factor) has a maximum value of two [4]. The transient analysis is used to determine the actual dynamic load factor, and to evaluate the accuracy of using a single-degree-of-freedom system to approximate the dynamic load factor at connections in a structure subjected to one or more failures.

## Transient Loading

To find the dynamic response values that the remaining reaction forces attain due to a loss of a support when the structure is under static loading, a transient analysis is performed. Load is applied in the form of two distinct load sets. One of the load sets will remain throughout the entire analysis cycle, while the other is the load set to be removed to represent failure of the support/connection. Recall that in general, the loading for both sets should be initially applied as a shallow ramp, followed by a brief portion of uniform loading, followed by the release of one of the load sets. Also recall Figure 10, which shows an example of how a typical load cycle is represented.

## Modal Analysis

In order to apply the initial ramp load, the period of the fundamental natural frequency for the example structure is required. As described in the transient failure analysis procedure section, the recommended ramp time should exceed 10 times the period of the fundamental frequency. A normal modes analysis of model 1, having all four supports present, yields a 1.3389 Hz. fundamental frequency. This fundamental frequency is associated with the first bending mode and is duplicated due to the symmetry of the problem. Figure 23 shows the frequencies and modes shapes for modes 1 through 4. For this example structure, the period of the fundamental frequency is 0.747 seconds. Therefore, a ramp time of 10 seconds is greater than 13 times the period, so transient response should be negligible during the ramp period and subsequent uniform load period.

## Transient Analysis

Model 2 is utilized to conduct the transient analysis by using the boundary conditions and loads shown in Figure 19. The loads at the free end are assigned to be load set #1, and the support load that

replaces point 4 is assigned to be load set #2. The load method depicted in Figure 2 is utilized to examine the transient response of this simple example. Both load sets are ramped from load factors of 0.0 at time  $t=0$  seconds to load factors of 1.0 at time  $t=10$  seconds. The two load sets remain at load factors of 1.0 until time  $t=12$  seconds. Load set #2 is ramped down to a load factor of 0.0 over the next 0.1 seconds to simulate failure of the connection at point 4, while load set #1 remains constant at a load factor of 1.0. From time  $t=12.1$  seconds until time  $t=20$  seconds, load sets #1 and #2 remain at load factors 1.0 and 0.0, respectively. To perform the analyses, a time step of 0.01 is chosen, and the damping coefficient is initially set to 0.04 (NASTRAN parameters  $G=0.04$  and  $W3=1.3$ ). Results are reported in the form of reaction forces as a function of time at the remaining three connections, point locations 1, 2 and 3 as shown in Figure 18.

Results for the transient analysis of the example structure are shown in Figures 24 to 26, which provide the connection forces at points 1, 2 and 3, respectively. The results indicate that the response is very stable up until load set #2 is released to simulate initial failure. Since it is necessary for the response to stabilize before the initial failure is introduced, this load introduction method is more desirable since it is “stable” throughout the ramp and uniform load periods. The length of the ramp is a function of the fundamental frequency period only, and the ending time is a function of the problem being examined. With experience, the ramp length, ending time, and time steps can be tailored to provide the required response in the least possible computation time.

### Comparison of Linear and Transient Response

Using the linear and transient analyses, a comparison is made between the linear and transient responses to determine the importance of dynamic effects. For the cantilever box structure examined in this simple example, Table 1 shows the linear analysis support forces at the points shown in Figure 18. Table 2 shows the transient analysis connection forces attained at  $t=12$  seconds,  $t=20$  seconds, and the maximum values computed after the reduction of load set #2 to simulate the failed support at point 4. Lastly, Table 3 shows the comparison of the connection forces after simulation of the failed support at point 4. The table shows the linear static analysis, transient analysis and single-degree-of-freedom approximation values. Recall that for a single-degree-of-freedom system, the dynamic load factor is 2.0 for an undamped system. The dynamic load factor applies to the difference between the value prior to the failure simulation and the value after failure simulation. That is, the maximum expected value based on a single-degree-of-freedom system is equal to the connection value prior to failure plus two times the difference between the value after failure and the value prior to failure. Mathematically this response is represented by:

$$F_{\text{maximum}, SDOF} = F_{\text{static}, \text{pre-failure}} + 2(F_{\text{static}, \text{post-failure}} - F_{\text{static}, \text{pre-failure}})$$

The calculated dynamic load factors from the transient analysis are also shown in Table 3. The dynamic load factor for a single connection component is defined for the transient failure analysis as:

$$\text{Dynamic Load Factor}_{TFA} = \frac{(F_{\text{transient}, \text{maximum}} - F_{\text{static}, \text{pre-failure}})}{(F_{\text{static}, \text{post-failure}} - F_{\text{static}, \text{pre-failure}})}$$

For the magnitude, or actually the difference vector, the dynamic load factor is defined as:

$$\text{Dynamic Load Factor}_{TFA} = \frac{\|(\bar{F}_{\text{transient}, \text{maximum}} - \bar{F}_{\text{static}, \text{post-failure}})\|}{\|(\bar{F}_{\text{static}, \text{post-failure}} - \bar{F}_{\text{static}, \text{pre-failure}})\|}$$

where the bar overscript indicates vector quantities.

Examination of Table 3 indicates that the dynamic load factor is dependent upon the location of the connection with respect to the failed connection, and can even differ slightly for each component examined at the connection. Also, notice that applying the single-degree-of-freedom (SDOF) dynamic load factor can lead to errors in excess of 25%. Therefore, it is necessary to perform a transient analysis to accurately predict connection loads after an initial failure is introduced. Additionally, since the dynamic load factor is dependent on the connection location, applying the SDOF dynamic load factor of two might lead to improper failure sequencing. In other words, it is not possible to apply simplified calculations based upon SDOF systems to approximate the system response. This is because the dynamic load factor is not uniform throughout the structure and can vary significantly from a value of two, even for this relatively simple example structure.

**Table 1: Linear analysis connection force (lbs) comparison for cantilever box structure with no failed supports and one failed support (point 4, see Figure 18)**

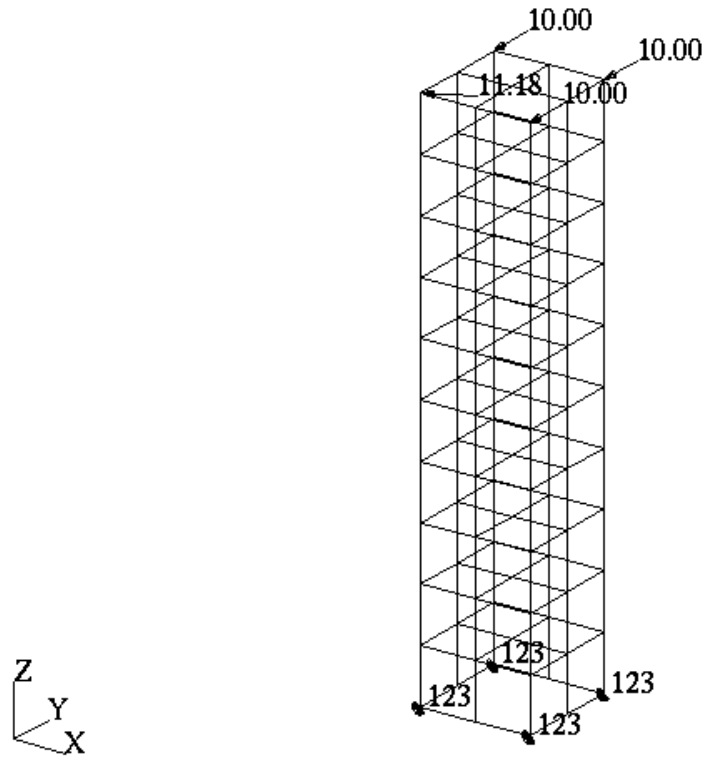
Location	Force	No Failure	Failure	Difference
Point 1	X	10.68	29.69	19.01
	Y	8.677	27.71	19.03
	Z	112.5	225.0	112.5
	Magnitude	113.3	228.6	115.3
Point 2	X	-1.936	17.04	18.98
	Y	8.824	-16.73	-25.55
	Z	62.50	-50.00	-112.5
	Magnitude	63.15	63.09	-0.06
Point 3	X	-5.683	-36.73	-31.05
	Y	5.071	24.02	18.95
	Z	-62.50	-175.0	-112.5
	Magnitude	62.96	180.4	117.5

**Table 2: Transient failure analysis connection forces (lbs) for the cantilever box structure with one failed support (point 4, see Figure 18)**

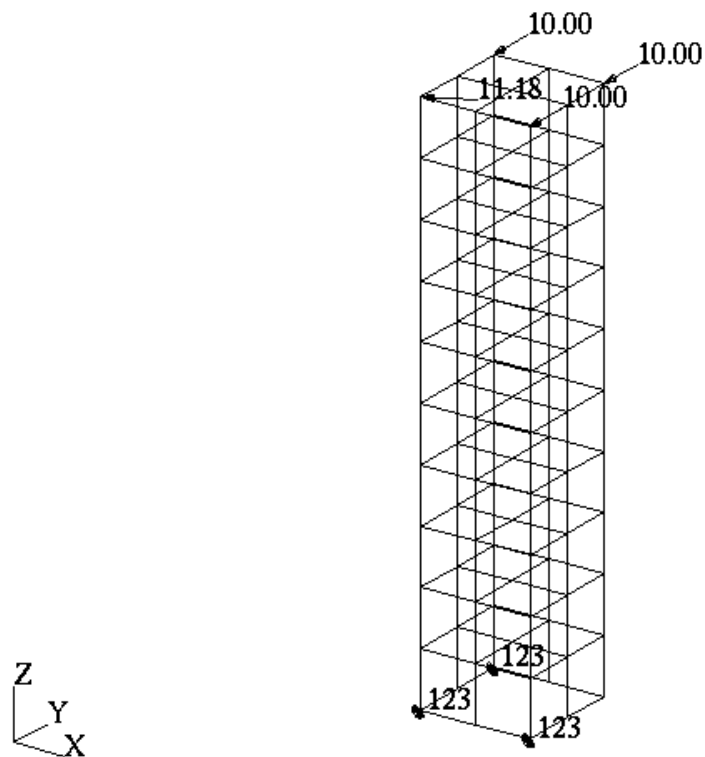
Location	Force	t=12 s	t=20 s	Maximum
Point 1	X	10.58	29.36	43.64
	Y	8.569	27.37	41.64
	Z	111.7	222.6	326.1
	Magnitude	112.5	226.1	331.6
Point 2	X	-1.981	16.78	27.55
	Y	8.656	-16.48	-26.96
	Z	62.34	-48.76	-101.4
	Magnitude	62.97	54.14	108.4
Point 3	X	-5.918	-36.46	-47.00
	Y	5.010	23.77	34.52
	Z	-62.50	-173.8	-226.4
	Magnitude	62.98	179.1	233.8

**Table 3: Comparison of maximum connection forces (lbs) and transient dynamic load factor for the cantilever box structure with one failed support (point 4, see Figure 18)**

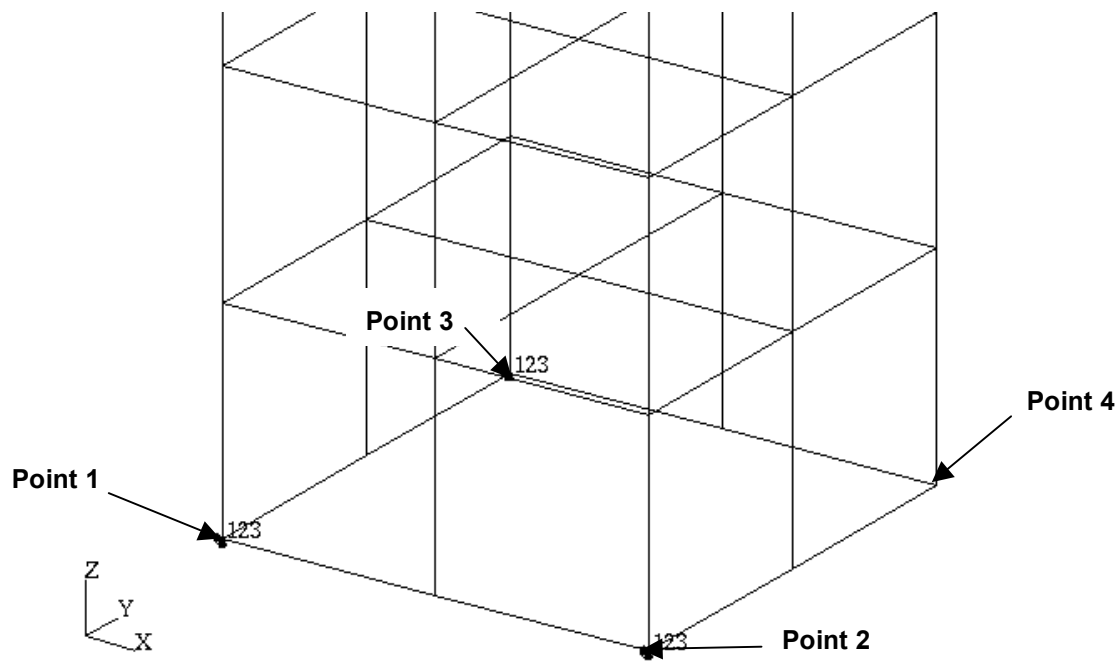
Location	Force	Transient Maximum	SDOF Approximation Maximum	Transient Dynamic Load Factor
Point 1	X	43.64	48.70	1.734
	Y	41.64	46.74	1.732
	Z	326.1	337.5	1.899
	Magnitude	331.6	343.9	1.890
Point 2	X	27.55	22.02	1.554
	Y	-26.96	-42.28	1.400
	Z	-101.4	-182.5	1.457
	Magnitude	108.4	63.03	1.457
Point 3	X	-47.00	-67.78	1.331
	Y	34.52	42.97	1.554
	Z	-226.4	-287.5	1.457
	Magnitude	233.8	297.8	1.451



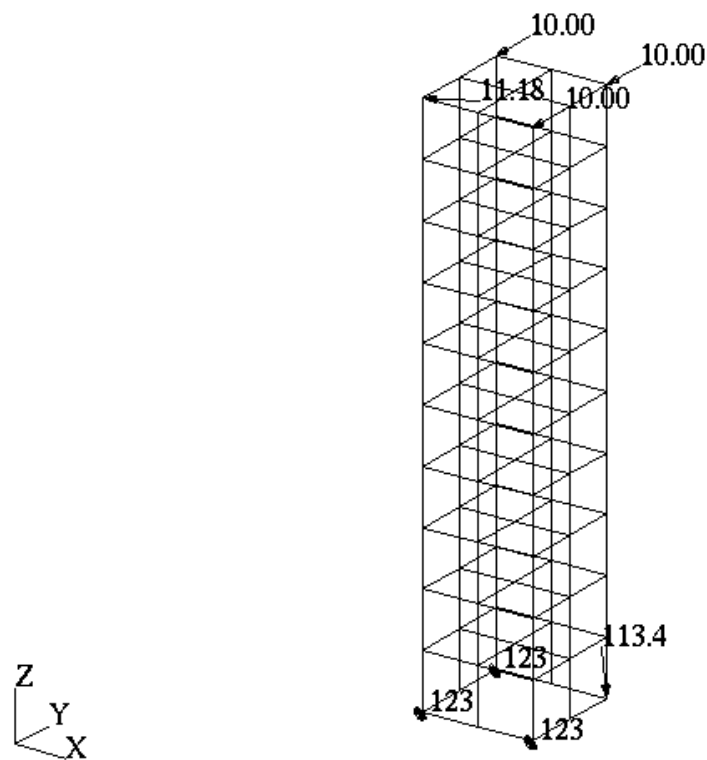
**Figure 16: Cantilevered box structure example with pinned corner point supports and tip corner loads (kips) (Model 1)**



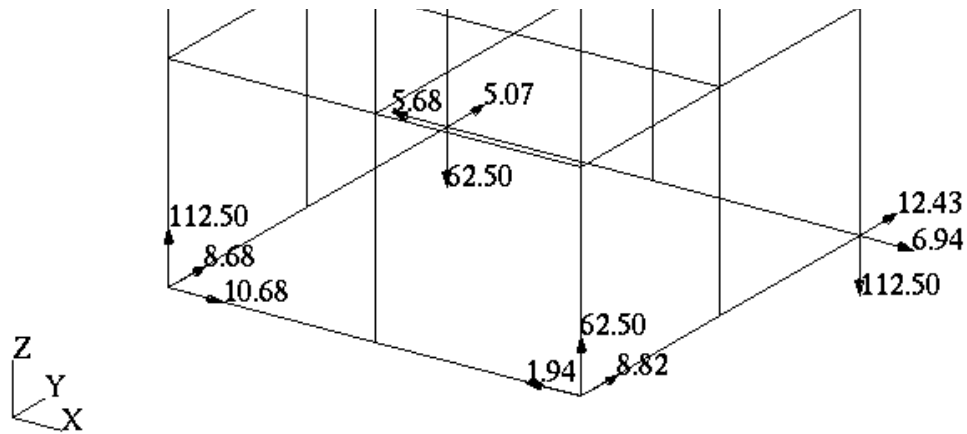
**Figure 17: Loads (kips) and boundary conditions for the example model with one support removed (Model 2)**



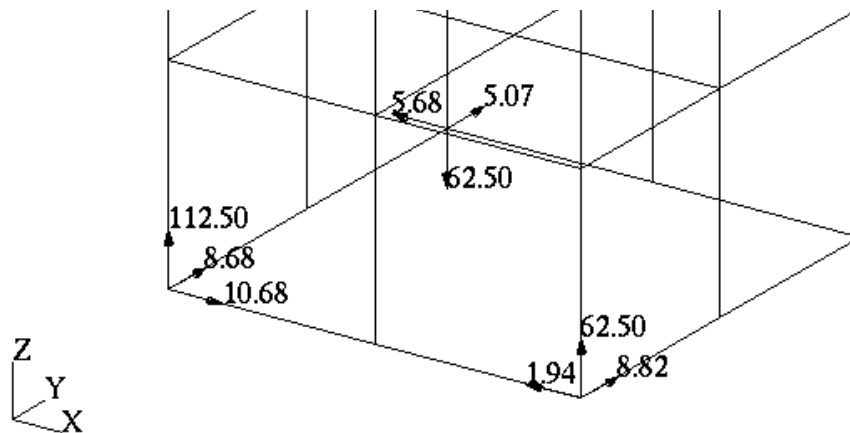
**Figure 18: Support point numbering convention**



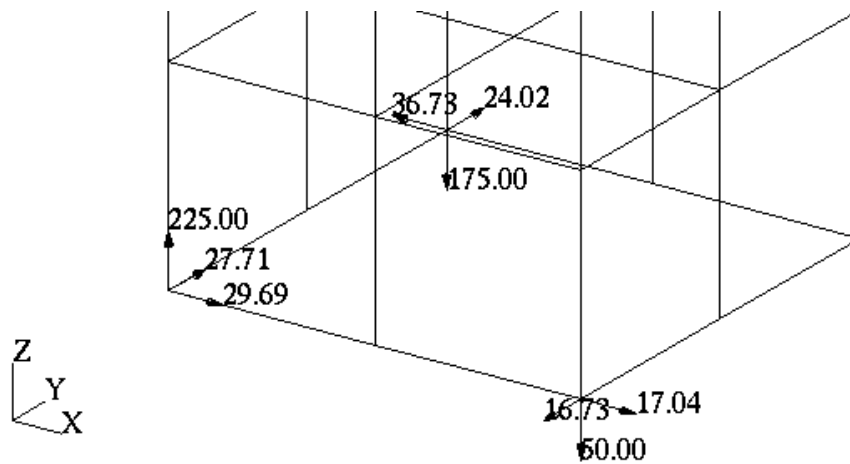
**Figure 19: Loads (kips) and boundary conditions for the example model with one support replaced by the reaction force (Model 2)**



**Figure 20: Linear static analysis reaction forces (kips) for loading/BCs of Figure 16**

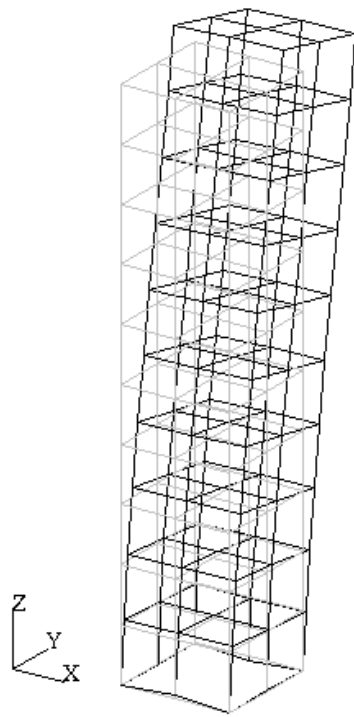


**Figure 21: Linear static analysis reaction forces (kips) for loading/BCs of Figure 19**

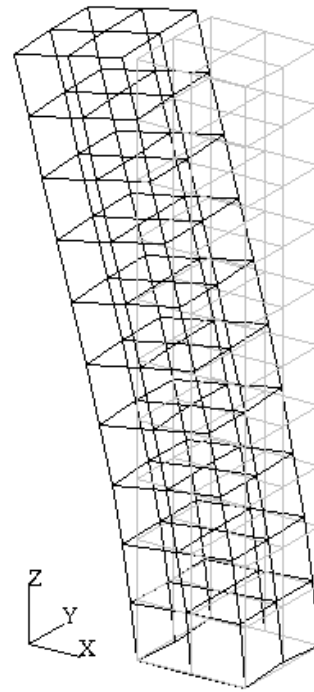


**Figure 22: Linear static analysis reaction forces (kips) for loading/BCs of Figure 17**

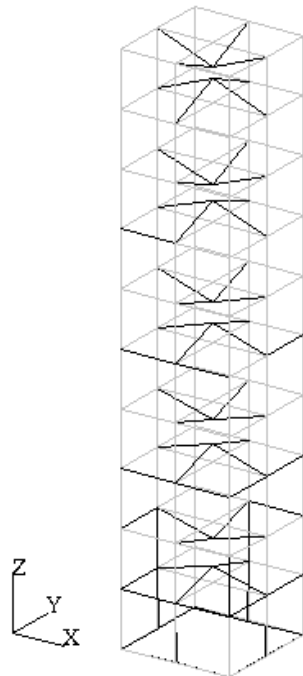




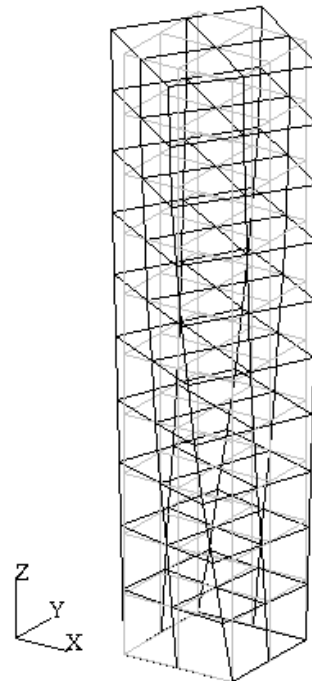
**Mode 1 (1.3389 Hz.)**



**Mode 2 (1.3389 Hz.)**

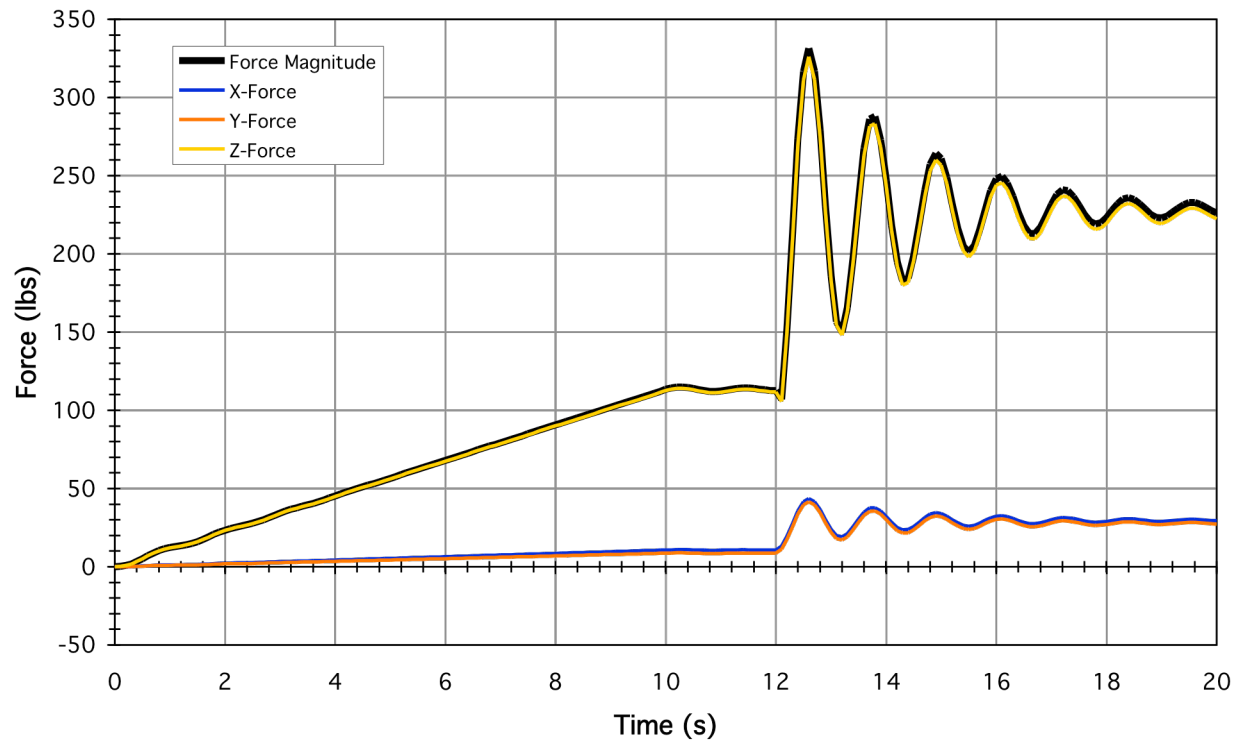


**Mode 3 (2.4578 Hz.)**

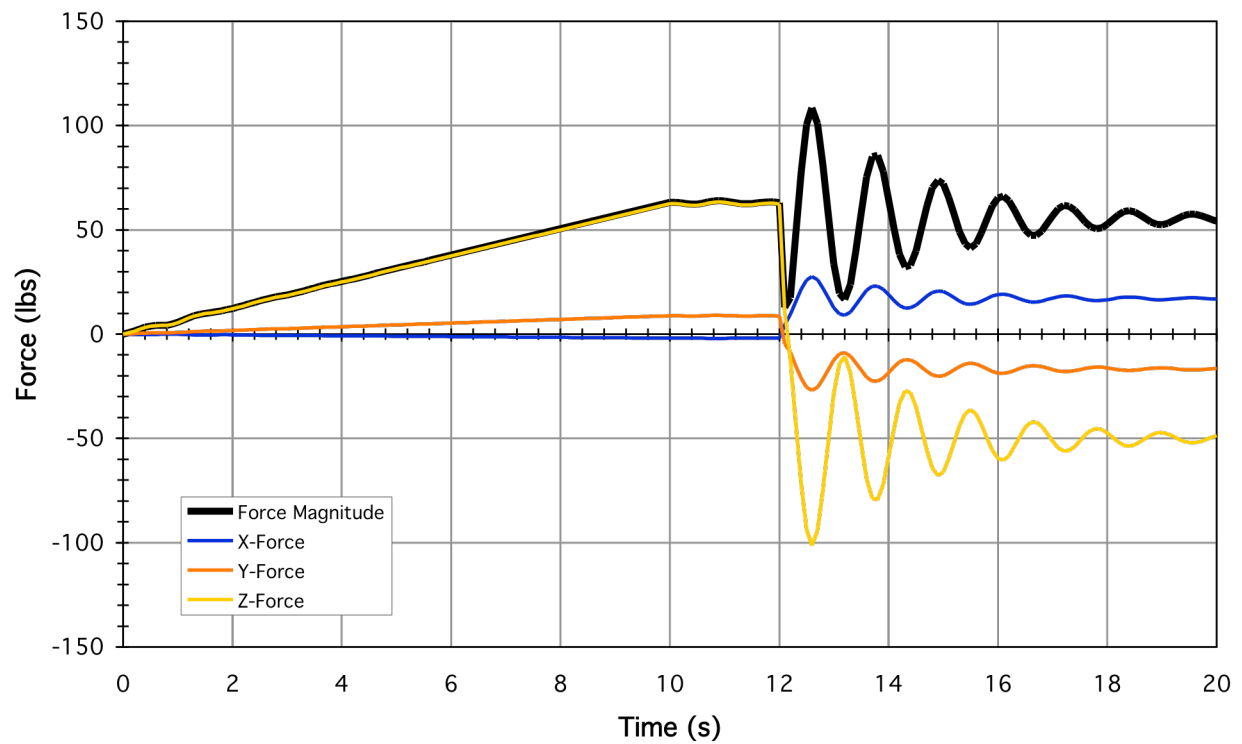


**Mode 4 (2.779 Hz.)**

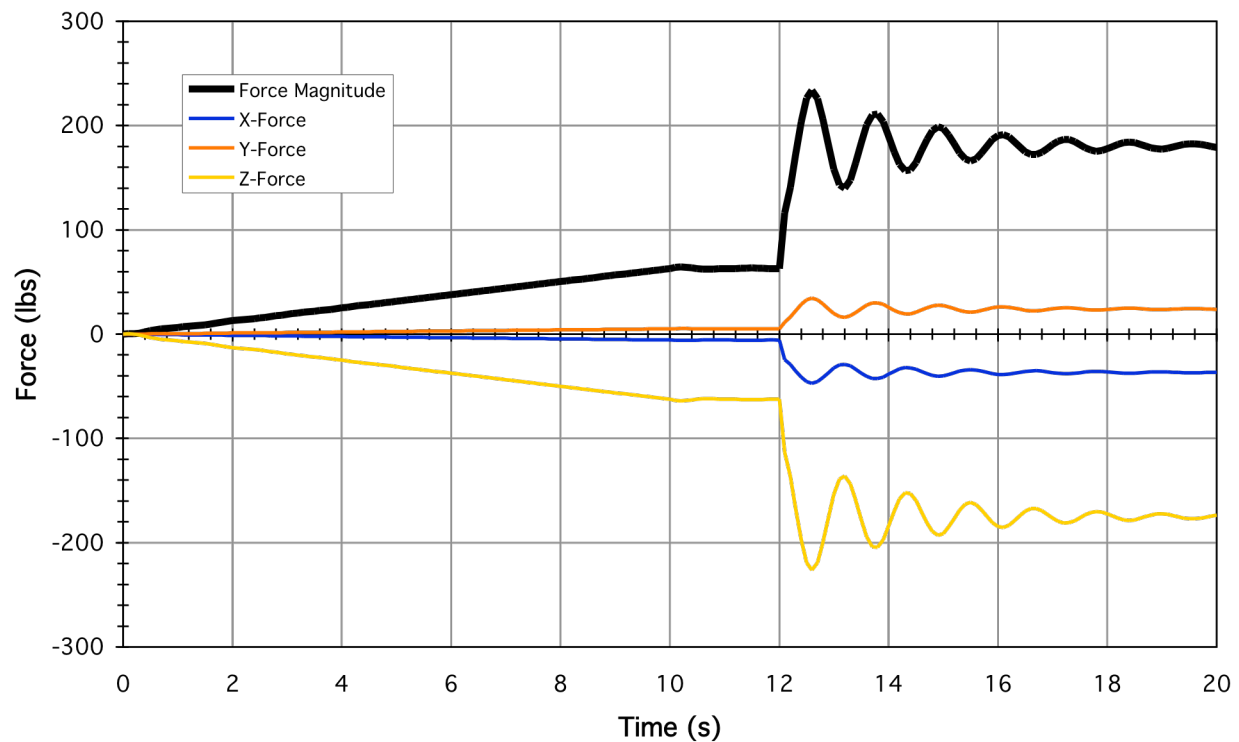
**Figure 23: Frequencies and mode shapes for Model 1**



**Figure 24: SPC reaction force response at point 1 for load method shown in Figure 2**



**Figure 25: SPC reaction force response at point 2 for load method shown in Figure 2**



**Figure 26: SPC reaction force response at point 3 for load method shown in Figure 2**

### Real World Example – AA587 Vertical Tail Plane

On November 12, 2001, an Airbus 300-600R being operated as American Airlines Flight 587 crashed soon after take-off from John F. Kennedy airport in New York City, killing all 260 persons aboard and 5 on the ground. The plane's composite vertical stabilizer and rudder separated from the aircraft before it impacted the ground. Initial analyses indicated that this accident was the first commercial aircraft crash that involved failure of primary structure made from composite materials. NASA Langley Research Center (LaRC) was asked by the National Transportation Safety Board to support the accident investigation because of LaRC's expertise in structural analysis and testing of composite structures and materials. The results of the NASA AA587 investigation are documented in References 5 and 6. As part of this investigation, the NASA AA587 Global Analysis Team was formed with the responsibility of assessing the global response of the vertical tail plane (VTP). Also as part of this investigation, the described transient failure analysis procedure was applied to the AA587 VTP to assist in failure scenario interrogation and failure sequencing. Details of the VTP failure analysis are provided in Reference 5 and are summarized in the following sections.

#### Physical Damage

The physical damage to the VTP is extensive, and includes the main attachment fittings, comprising the main lugs and shear yokes. The six main lugs are integral with the skin and attach the VTP to the fuselage, and provide primarily in-plane support. Transverse support is primarily provided by the six shear yokes that connect the spar ends to the fuselage. Damage is also present at the rudder/fin connections and within the rudder itself. Figures 27-29 illustrate some of the observed damage.

## Initial Failure

Static analyses were carried out for various AA587 accident event loads as identified from the flight data recorder (FDR) information. Figure 30 shows the VTP root bending moment as a function of time (arbitrary  $t=0$  value chosen). Analyses were conducted at the points marked Max A, Max B and Max C in the figure using flight loads that were developed from the FDR data using several methods. Analyses utilized the finite element model shown in Figure 31 with the global coordinate frame as indicated. VTP response was compared to the main attachment fitting allowables given in Table 4 and to various strain allowables for 5 failure scenarios. Initial failure was identified as the right rear lug under the Max C load condition with a reserve factor ranging from 0.95 to 1.1, depending on the flight load development method used. The VTP attachment fitting forces for the Max C load condition that yielded the lowest reserve factor ( $RF=0.95$ ) are shown in Table 5 with the critical value at the right rear lug shown in red and highlighted in yellow. Therefore, the failure scenario interrogation indicates that the most likely initial failure was a tension failure of the right rear lug, a failure that is consistent with the observed physical evidence in that region. Failure at this Max C condition is equivalent to a load factor of at least 1.92 times design limit load, which exceeds the certification requirement that the component must be able to sustain a load factor of 1.5 times design limit load without catastrophic failure.

## Transient Failure Analysis

Failure sequencing of the AA587 VTP, both static and transient, is carried out using the Max C load condition (see Figure 30), and the applied loads are held constant throughout the analyses. The initial failure is assumed to be a tension failure of the right rear lug. Additional static analyses with connections modeled to simulate sequential failures indicate a progression of damage in the fin, predominantly at the fin-to-fuselage connection points. However, none of these progressive static failure analyses provided any insight regarding the physical damage observed on the rudder. Therefore, the developed transient failure analysis procedure is applied, post initial right rear lug failure, to determine if any of the observed rudder damage can be explained by these dynamic effects.

The time-dependent response of the AA587 VTP as various connections failed is simulated using the transient failure analysis procedure. Responses are computed as a function of time, the responses are compared to allowables, and successive failures are determined. Various types of failure, such as main fitting failure, fin or rudder skin failure, rudder fitting failure, bolted connection failure, etc., are examined, and the transient failure sequence is established. A typical main attachment fitting force-time history plot, in this case for the left rear yoke, is shown in Figure 32 where the time scale is set to zero at initial failure of the right rear lug. The left rear yoke is identified as the second failure in the sequence (i.e., the first failure after the right rear lug) using the allowable main attachment fitting values shown in Table 4. To find the third and subsequent failures, the left rear yoke load time history is replaced by the approximated time history shown in Figure 33. The markers in the figure indicate the load values used in the tabular input to represent the left rear yoke load time history during the subsequent transient analyses. Lastly, a typical rudder skin strain plot after multiple failures have occurred is shown in Figure 34.

The failure sequence determined using the transient analyses is identical to the static sequence through the fifth failure as shown in Fig. 33. However, the transient analysis suggests that the sixth failure is the first rudder failure in the form of skin failure in the region of hinge fitting #1 (recall Fig. 32). The transient analyses also shows that there are many locations in the rudder that exhibit significant load variation due to dynamic effects, contrary to what was seen in the sequential static analyses in which the rudder and rudder hinge line forces remain nearly constant. The significant changes to the rudder response observed in the transient analyses, in conjunction with the physical evidence of the rudder damage, suggest that dynamic effects are present and contribute to the observed damage. Based upon the transient analysis, skin failure at the rudder hinge fitting #1 region is likely the first rudder failure that leads to the remaining rudder failures. Additionally, it is seen that dynamic effects can significantly increase the rudder attachment fitting/hinge arm/actuator forces at numerous other fittings. Therefore, the developed transient failure analysis procedure is used to demonstrate that a reasonable possibility exists that the

dynamic effects, post first failure at the right rear lug, can cause subsequent failure in the rudder and thus explain the presence of the observed rudder damage.

**Table 4: Lug and shear yoke allowable strengths**

Component	Tension Strength (N)	Compression Strength (N)
Front Lug	730,000	> 730,000 <sup>a</sup>
Center Lug	1,040,750	> 1,040,750 <sup>b</sup>
Rear Lug	902,000	1,003,000
Front Shear Yoke	73,700	73,700
Center Shear Yoke	90,900	90,900
Rear Shear Yoke	152,000	152,000

a) Provided by Airbus to be greater than 520,360 from test, but taken to be at least equal to tension as per rear lug.

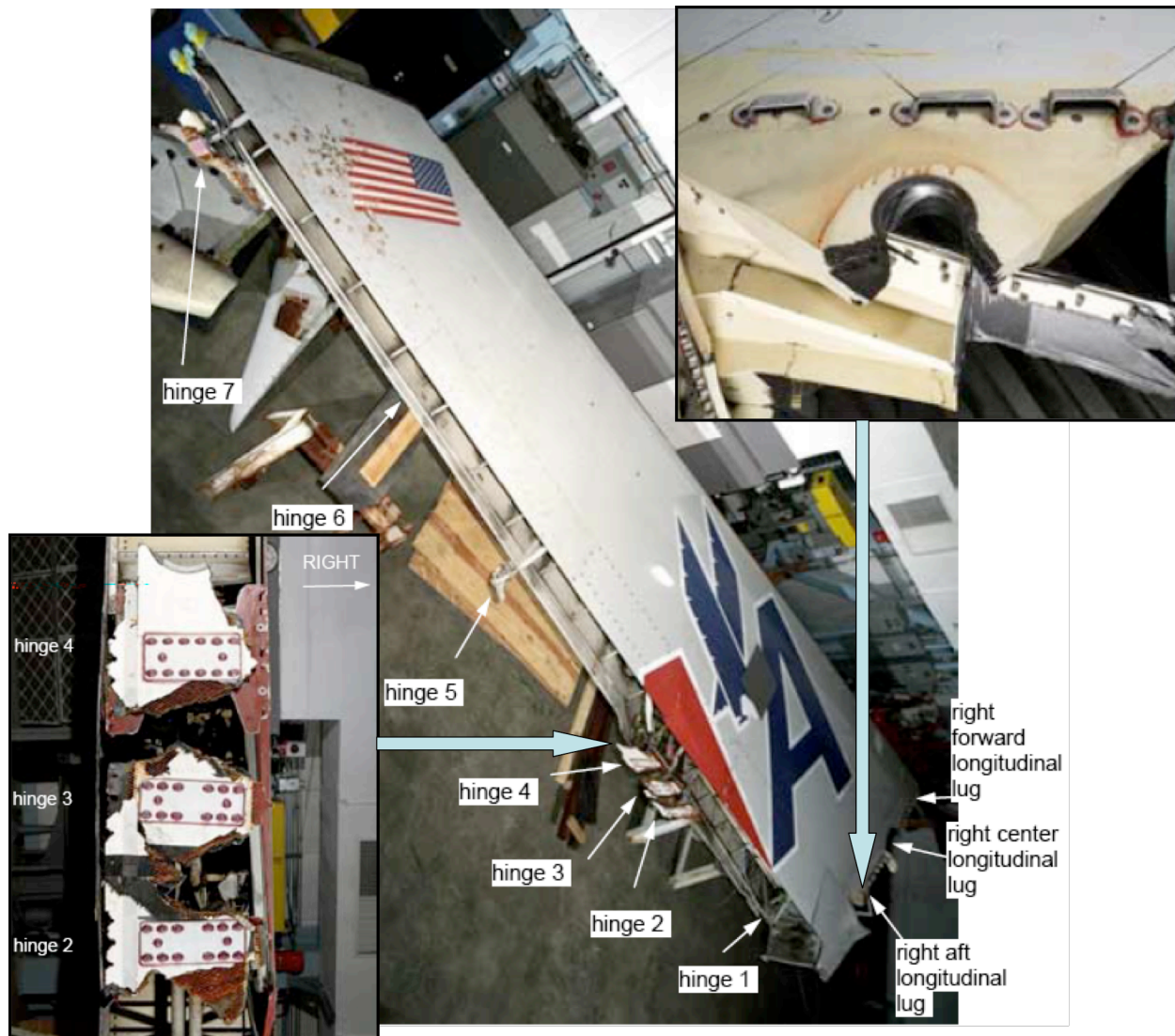
b) Provided by Airbus to be greater than 761,640 from test, but taken to be at least equal to tension as per rear lug.

**Table 5: Linear analysis lug and yoke forces, in global coordinate system, for the Max C load condition**

	Main Fittings (Lugs)					
	Front		Center		Rear	
	LHS	RHS	LHS	RHS	LHS	RHS
<b>Fx (N)</b>	231468	-251798	258898	-270943	409483	-384931
<b>Fy (N)</b>	15896	12663	56014	35503	69413	36019
<b>Fz (N)</b>	298228	-316005	715392	-717066	895060	-867431
<b>Fxz (N)</b>	377514	404056	760798	766547	984281	<b>949004</b>
<b>Fres (N)</b>	377849	404254	762857	767369	986725	949688
<b>Mx (N*m)</b>	-3200	-2446	-10466	-5991	-13290	-7055
<b>Mz (N*m)</b>	-256	57	883	323	5001	2227

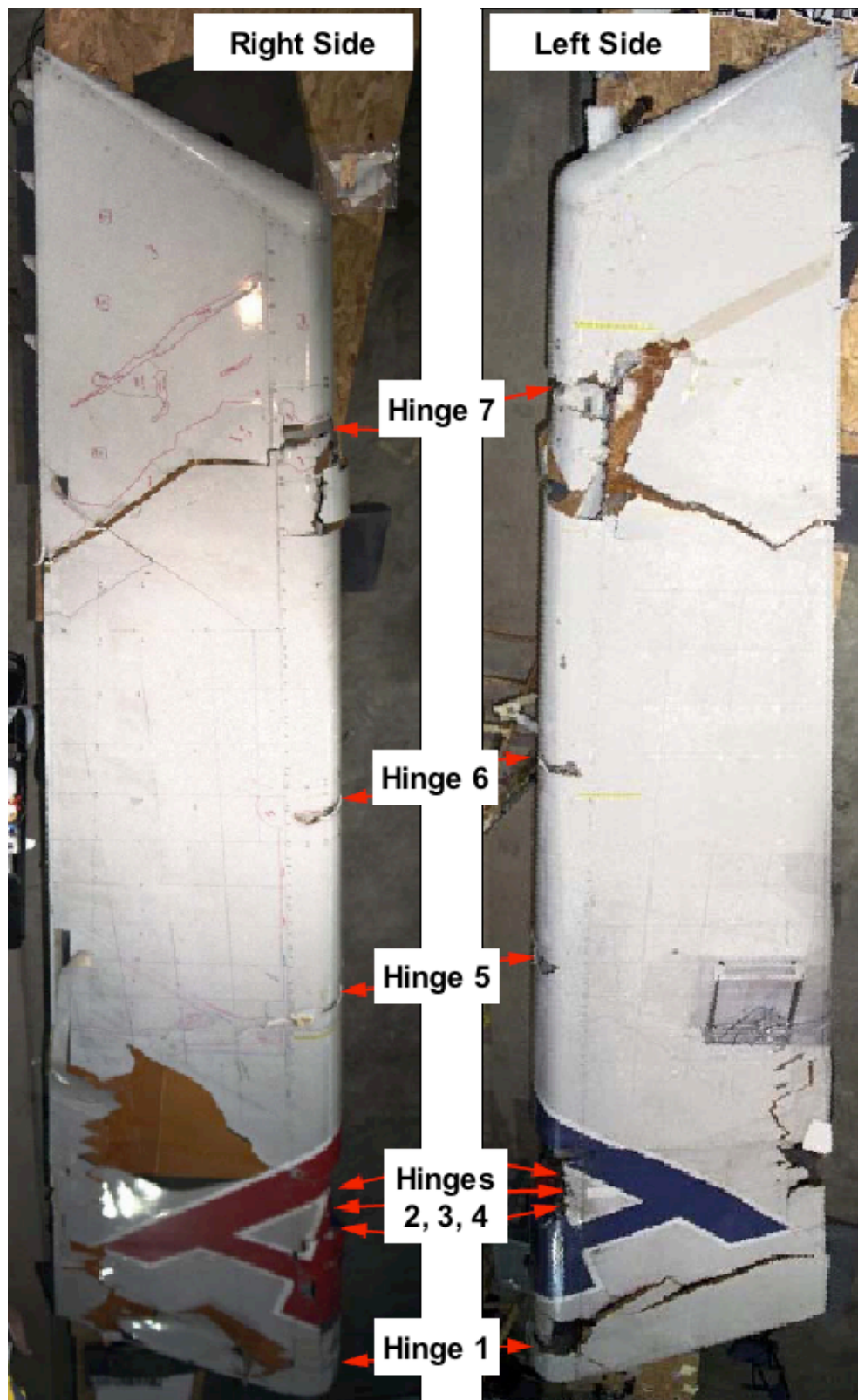
  

	Shear Fittings (Yokes)					
	Front		Center		Rear	
	LHS	RHS	LHS	RHS	LHS	RHS
<b>Fx (N)</b>	-794	807	-160	10	-10400	8828
<b>Fy (N)</b>	10692	10860	2190	132	85445	72530
<b>Fz (N)</b>	-904	918	-244	15	-15868	13470
<b>Fres (N)</b>	10759	10928	2210	133	87526	74297

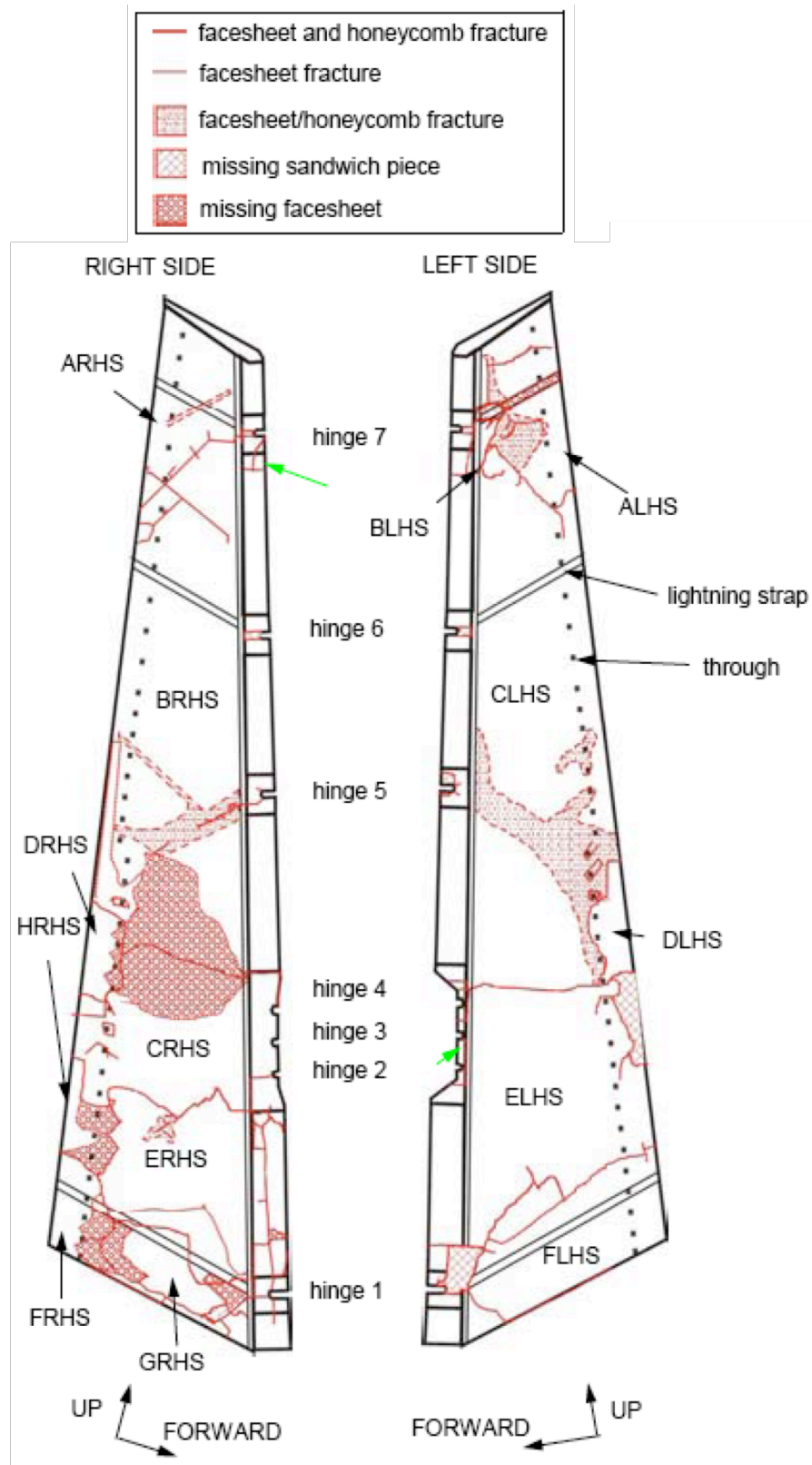


**Figure 27: Fin and rudder hinge line damage of AA587**



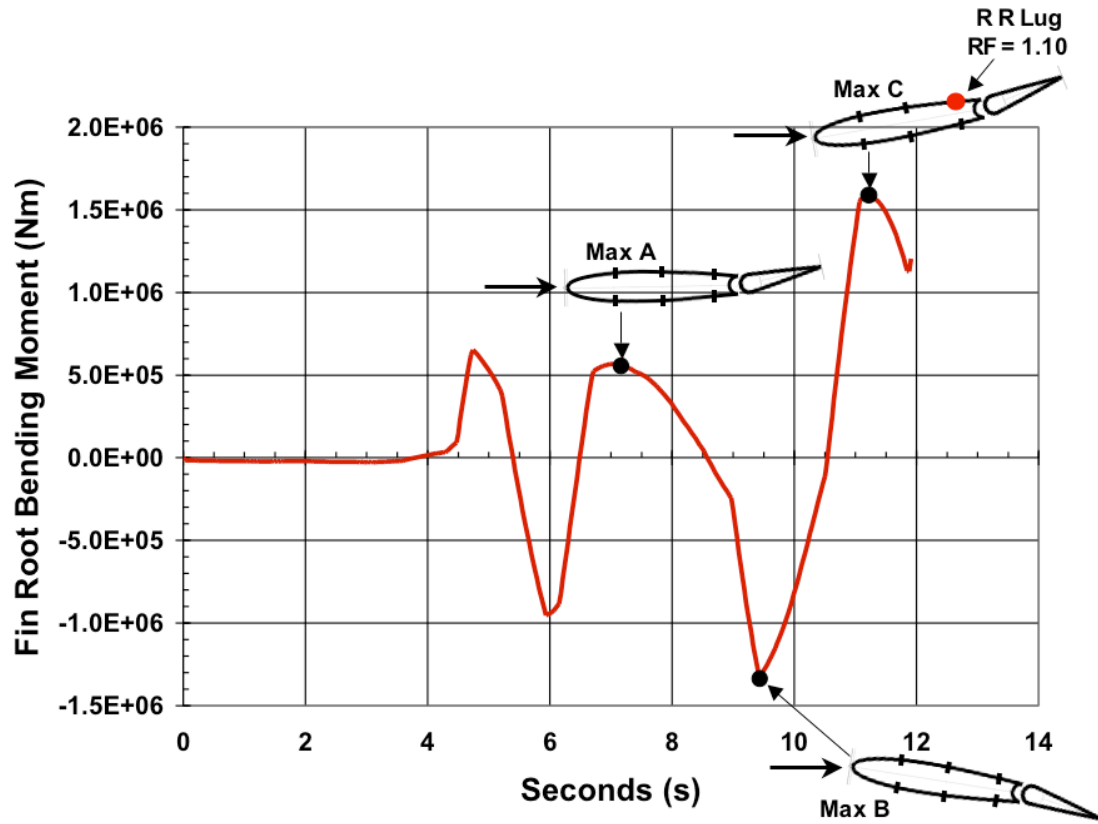


**Figure 28: Rudder damage of AA587**

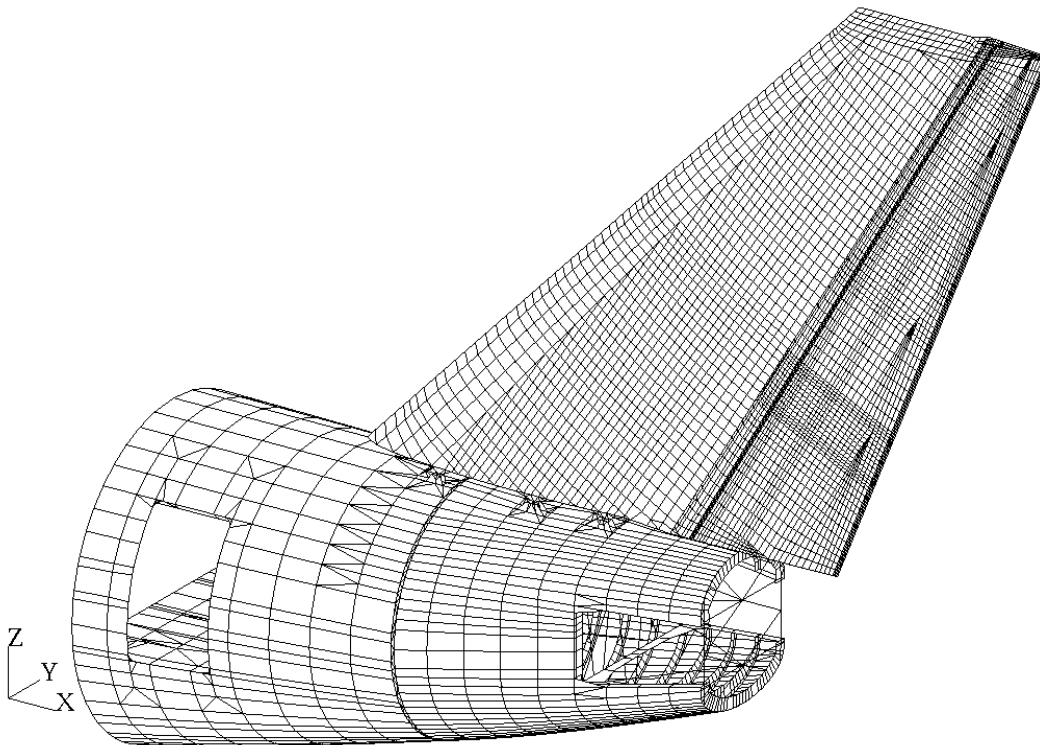


**Figure 29: Sketch of rudder damage of AA587**

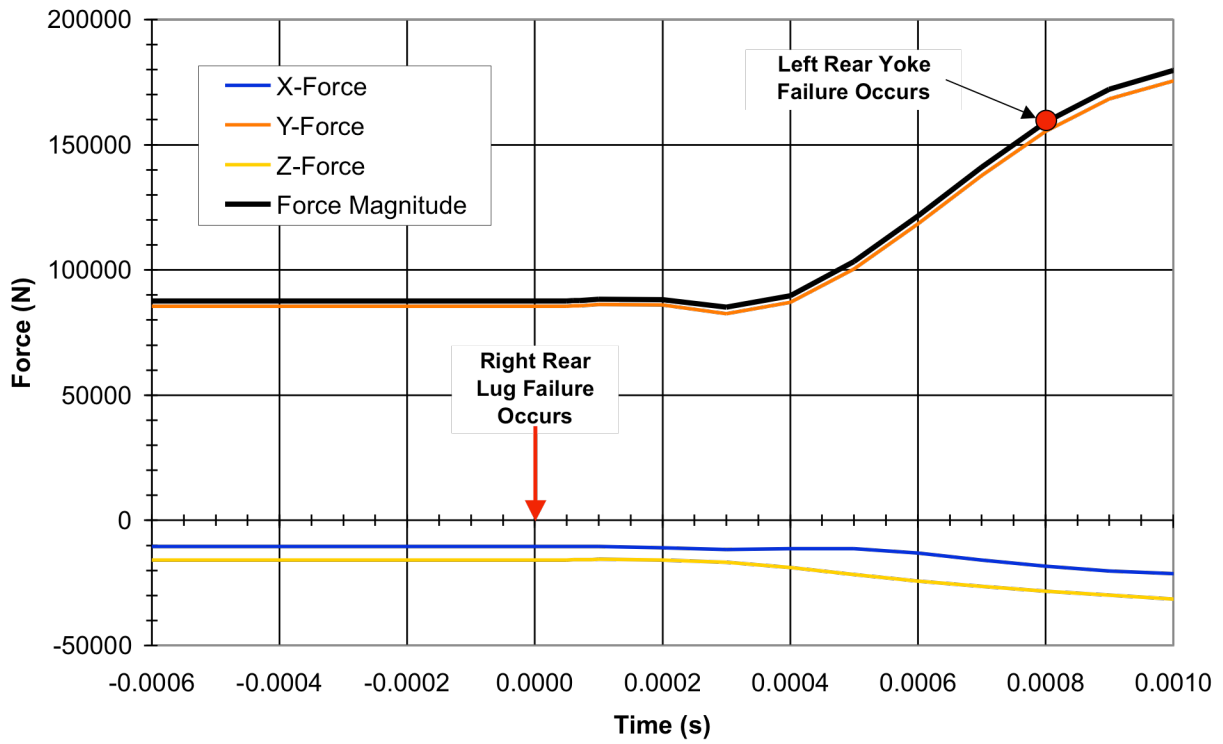




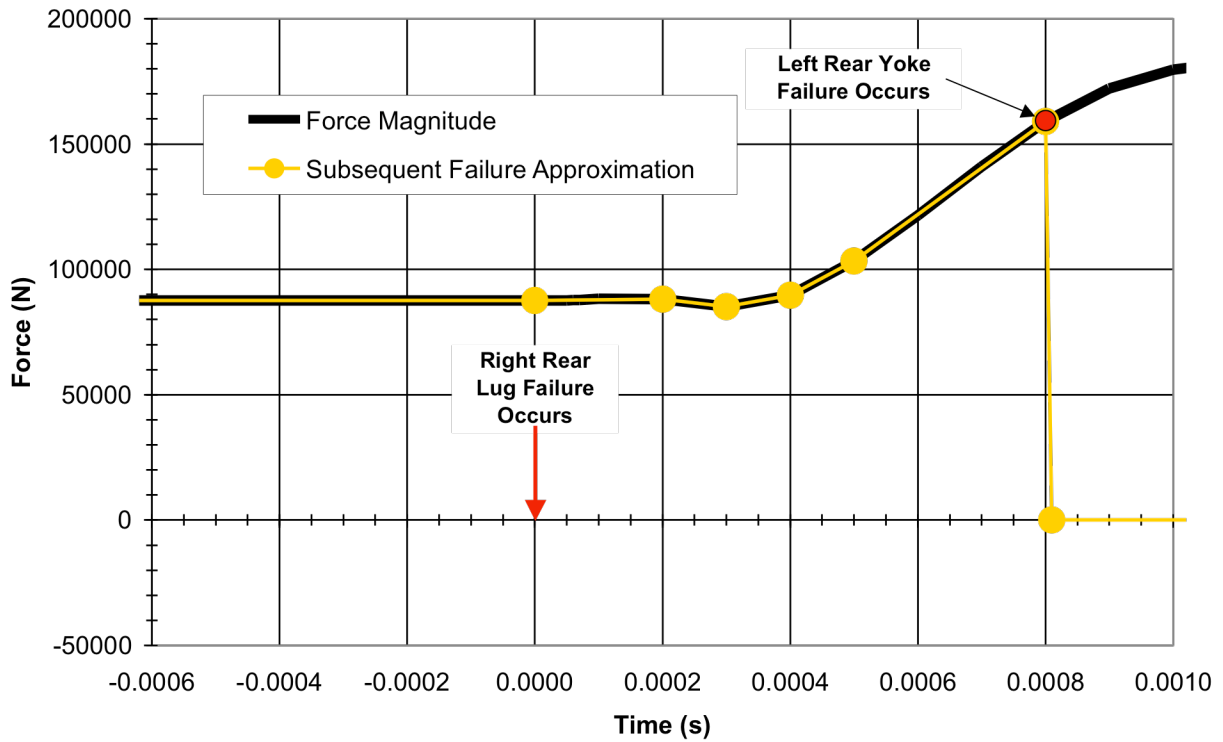
**Figure 30: Primary loading on VTP during accident event**



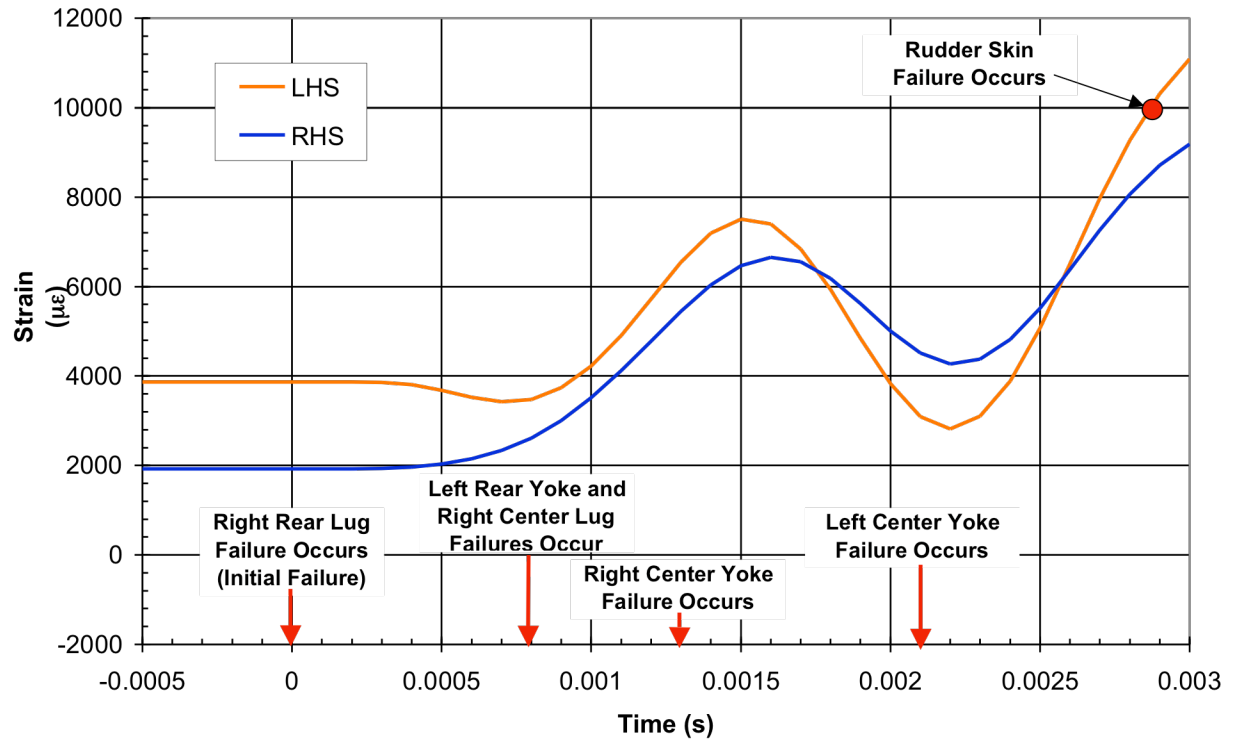
**Figure 31: Fuselage tail section and VTP finite element model and coordinate system**



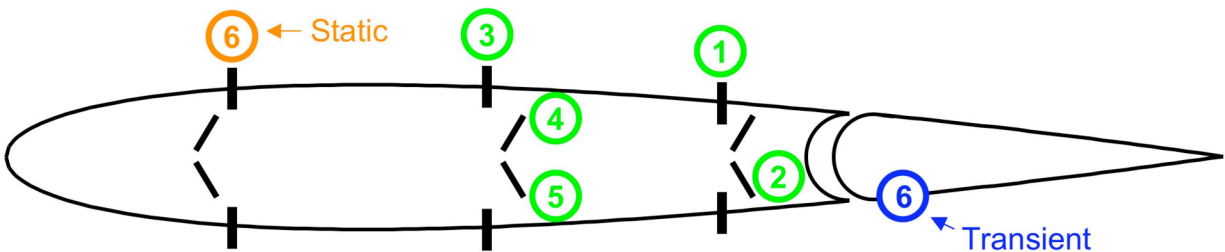
**Figure 32: Left rear yoke forces**



**Figure 33: Approximation plot of left rear yoke force for subsequent failure analyses (markers indicate values used in tabular load input)**



**Figure 34: Inner surface rudder skin strains,  $\varepsilon_{xx}$ , in region of hinge fitting #1**



**Figure 35: Transient failure sequence (green number indicates sequence for both static and transient analysis, orange indicates static, and blue indicates transient)**

## Conclusion

A transient failure analysis procedure was developed to examine the dynamic effects that result from introducing a discrete failure while a structure is under static load. The failure is introduced by replacing a connection load history by a time-dependent load set that removes the connection load at the time of failure. The subsequent transient response is examined to determine the importance of the dynamic effects by comparing the structural response with the appropriate allowables. Additionally, this procedure utilizes a standard finite element transient analysis that is readily available in most commercial software, permitting the study of dynamic failures without the need to purchase software specifically for this purpose.

## References

- <sup>1</sup>MSC.NASTRAN 2004 Release Guide, MSC.Software Corporation, Santa Ana, California, 2003.
- <sup>2</sup>MSC.NASTRAN Version 68 Basic Dynamic Analysis User's Guide, MSC.Software Corporation, Santa Ana, California, 2002.
- <sup>3</sup>MSC.NASTRAN Version 70 Advanced Dynamic Analysis User's Guide, MSC.Software Corporation, Santa Ana, California, 2002.
- <sup>4</sup>Craig, Roy R., Jr., *Structural Dynamics: An Introduction to Computer Methods*, John Wiley & Sons, Inc., New York, 1981.
- <sup>5</sup>Young, Richard D., Lovejoy, Andrew E., Hilburger, Mark W., and Moore, David F., "Structural Analysis for the American Airlines Flight 587 Accident Investigation – Global Analysis", AIAA 2005-2254, 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, 18 - 21 April 2005, Austin, Texas.
- <sup>6</sup>Raju, Ivatury S., Davila, Carlos G., Glaessgen, Edward H., Krishnamurthy, Thiagaraja, and Mason, Brian H., "NASA Structural Analysis Report on the American Airlines Flight 587 Accident– Local Analysis of the Right Rear Lug, AIAA 2005-2255, 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, 18 - 21 April 2005, Austin, Texas.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b></p>					
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE		3. DATES COVERED (From - To)	
01- 01 - 2007		Contractor Report			
4. TITLE AND SUBTITLE A Procedure for Modeling Structural Component/Attachment Failure Using Transient Finite Element Analysis				5a. CONTRACT NUMBER	
				NNL04AA10B	
				5b. GRANT NUMBER	
6. AUTHOR(S)  Lovejoy, Andrew E.				5c. PROGRAM ELEMENT NUMBER	
				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
				561581.02.08.07	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001				10. SPONSOR/MONITOR'S ACRONYM(S)  NASA	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA/CR-2007-214540	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 39 Availability: NASA CASI (301) 621-0390					
13. SUPPLEMENTARY NOTES Langley Technical Monitor: Dawn C. Jegley An electronic version can be found at <a href="http://ntrs.nasa.gov">http://ntrs.nasa.gov</a>					
14. ABSTRACT  Structures often comprise smaller substructures that are connected to each other or attached to the ground by a set of finite connections. Under static loading one or more of these connections may exceed allowable limits and be deemed to fail. Of particular interest is the structural response when a connection is severed (failed) while the structure is under static load. A transient failure analysis procedure was developed by which it is possible to examine the dynamic effects that result from introducing a discrete failure while a structure is under static load. The failure is introduced by replacing a connection load history by a time-dependent load set that removes the connection load at the time of failure. The subsequent transient response is examined to determine the importance of the dynamic effects by comparing the structural response with the appropriate allowables. Additionally, this procedure utilizes a standard finite element transient analysis that is readily available in most commercial software, permitting the study of dynamic failures without the need to purchase software specifically for this purpose. The procedure is developed and explained, demonstrated on a simple cantilever box example, and finally demonstrated on a real-world example, the American Airlines Flight 587 (AA587) vertical tail plane (VTP).					
15. SUBJECT TERMS Composite; Dynamic; Time-dependent; Transient Analysis					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: <a href="mailto:help@sti.nasa.gov">help@sti.nasa.gov</a> )
U	U	U	UU	41	19b. TELEPHONE NUMBER (Include area code) (301) 621-0390